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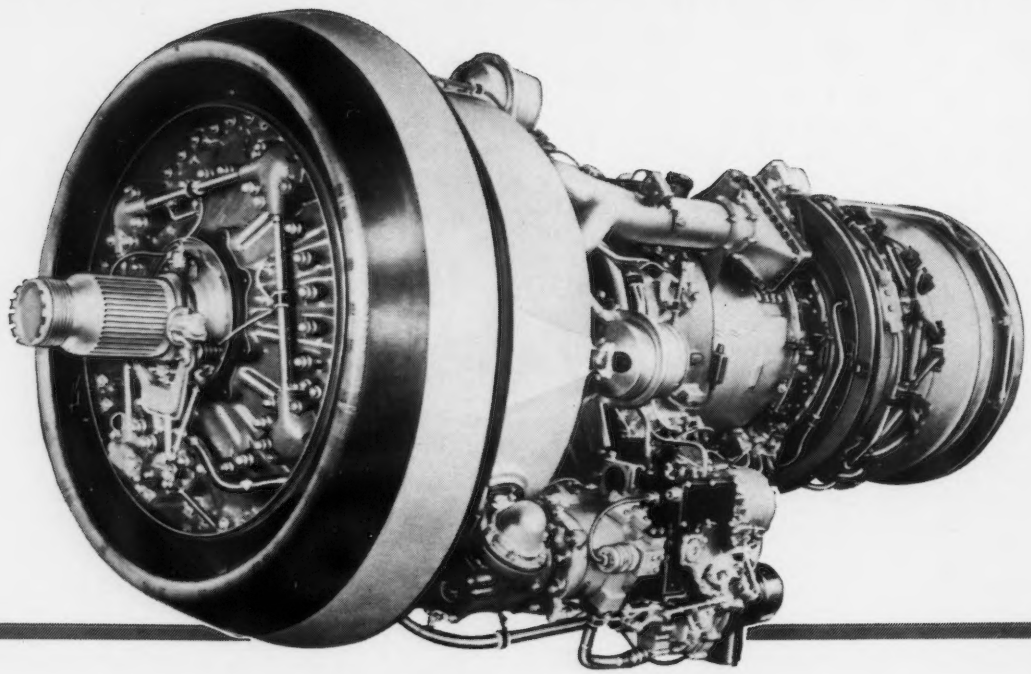

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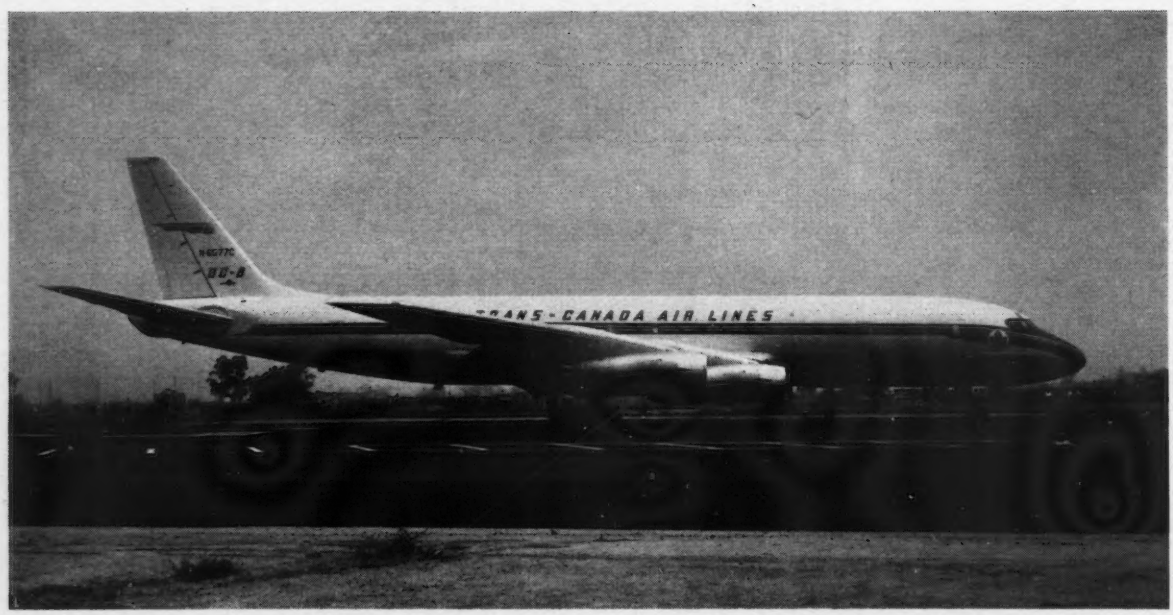
T.C.A.'s DC-8



The Douglas DC-8 (powered by four Rolls-Royce Conway engines) was recently put into service by Trans-Canada Air Lines.

EDITORIAL

THE INDUSTRIAL COUNTER-REVOLUTION

A GREAT deal of thought, and even some wisdom, has been expended in recent years on sophisticated analyses designed to shed some light on the process by which a nation may convert an economy which is primarily agrarian into an economy which is primarily industrial. This of course has present day reference to some of the underprivileged nations of the world and, historically, to processes which have come to be known euphuistically as Industrial Revolution.

It appears to be right that nations of the free world should aid underdeveloped nations to achieve this transformation irrespective of inclination or aspiration, and it is to be assumed that the benefits conferred by industrial revolution are in fact benefits; benefits that have the likeness of a sacrament and put the recipient nation in a state of economic grace.

It is perhaps this likeness that has tended to colour the process with the attributes of an irreversible change, and the irreversibility may well be true for major Powers committed to global preeminence. It is certainly not true for small nations caught in a battle for export markets between industrial giants, and it is particularly not true when the normal economic rules governing the contest have been abandoned in favour of pure political expediency and massive technological advance is rooted directly in the Government Treasury of great nations.

The first effect on the small nations must inevitably appear to be a recession, but with a difference.

The classical type of recession was a political-economic phenomenon poorly understood by politicians and explained in a dozen different ways by economists. But at least when it was over it only left scars behind. A reversal of the industrial revolution process must leave a nation permanently or semi-permanently maimed, its technology incapable of competition on any terms and its fixed production equipment anachronistic and uneconomic.

The nations of the West all pay substantial lip-service or better to the doctrine of free enterprise together with those social concomitants which allow those nations to call themselves the free nations of the world. It is therefore essential that free enterprise remains free and equally or perhaps more essential, that it remain enterprising. Enterprise in the field of influences created by industrial counter-revolution must take a quite different form from that which it has assumed in the past.

Industry must lean more heavily on basic Government economic and industrial policy, industry must also become more cohesive and cooperative. Government must show more creative industrial initiative and provide a pattern of economic incentive for both capital and people. Scientists and technologists must learn that national economic survival takes first place and in their relations with allied nations they must take every measure to integrate their working with programmes of major technological advance developing elsewhere.

The lessons to be learned are many and varied and it has been truly said that the future will hold many trials of nations' ability to find new forms of internal organization and international relationship. This is adaptation in the Darwinian tradition and the old rule is still valid – adapt or perish.

F.T.

AN APPRAISAL OF SYNTHETIC LUBRICANTS IN AIRCRAFT GAS TURBINES†

by J. P. Perry*

Imperial Oil Limited

SUMMARY

Aircraft gas turbine engines have created lubrication demands which are unique compared with those of the piston engine. The inability of conventionally refined petroleum oils to satisfy both low and high temperature requirements resulted in the development of ester base synthetic oils. This paper reviews the historical development of those lubricants in the light of changing engine requirements.

Millions of engine hours have been accumulated by gas turbines lubricated with synthetic oil. The unprecedented performance record of this oil in commercial airlines will be discussed. The review covers the period from the introduction of the Viscount in 1953 to the end of the first year's operation of the jet transports.

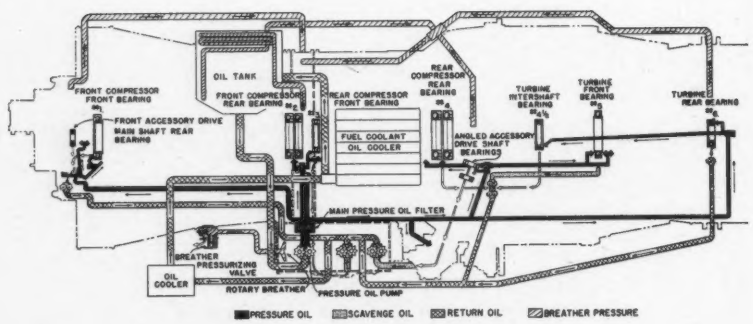


Figure 1
Lubrication system — Pratt & Whitney aircraft J-57

INTRODUCTION

WHITTLE's first aircraft gas turbine was relatively simple, commercially available kerosene providing the source of thrust and aviation piston engine oil the lubricant. The recognition by military authorities of this propulsive medium had become firmly established by the end of World War II and its potential for commercial transport aircraft was an additional incentive to its subsequent development. Progress was rapid and the output of jet engines increased from approximately 1,600 lb to approximately 16,000 lb for a ten-fold increase in the ten year period from 1946 to 1956. Accompanying better performance were higher temperatures, higher gear and bearing loads, operation at higher altitudes and the necessity for improved materials.

Since all heat engines reject a percentage of their power as waste heat, higher outputs meant higher thermal stresses on the lubricant. The increases in gear train loads demanded a lubricant possessing equivalent properties to a Grade 1100 aviation piston engine oil (i.e. 20 cs at 210°F) while still retaining good low temperature starting characteristics. Early engines were satisfied by a low viscosity petroleum oil (10-15 cs at 100°F), but as outputs increased, it became evident that this type of oil was too volatile and lacked high temperature lubricity. Attention was, therefore, directed to certain synthetics with superior load carrying and viscosity temperature characteristics. Research culminated in successful formulations which have been a major contribution in the development of high output engines. However, there are indications that the currently available synthetic oils do not have adequate thermal and oxidation stability for some engines now on the design board or under development. Improved synthetic oils will, therefore, be necessary to meet these new severity levels.

Millions of engine hours have been accumulated by gas turbines lubricated by synthetic oil in military and civil service, the performance to date having been highly successful.

BASIC OPERATING PRINCIPLES

The aircraft gas turbine differs markedly from the reciprocating engine. The piston engine develops its propulsive force by the conversion of heat energy into mechanical energy which is used to turn a propeller. Propulsion is obtained by imparting a small amount of acceleration to a large mass of air. The gas turbine, in its basic turbojet configuration, imparts a relatively large amount of acceleration to a smaller mass of air, and thus produces thrust or propulsive force directly.

To operate efficiently, the compressor-turbine assembly in a gas turbine must move very large masses of air at the highest possible temperature that materials will withstand. The heavy rotors are supported on a series of bearings which transmit both thrust and radial loads. In addition, auxiliary gears extract power from the main shaft. A portion of the transmitted power generates heat in the bearings and gears and this must be removed.

†Paper read at the Mid-season Meeting of the C.A.I. in Edmonton, on the 19th February, 1960.
*Technical Service Aviation Representative

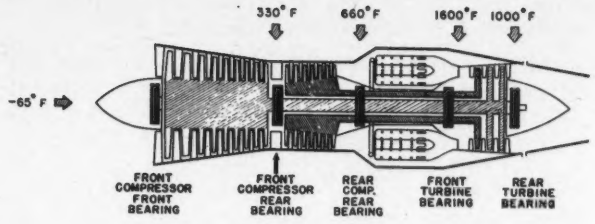


Figure 2
Jet engine temperatures

LUBRICATION SYSTEMS

In performing its dual functions of lubricating and cooling, the oil in a gas turbine must be supplied at the desired pressure and in the correct quantities to bearings supporting the compressor, turbine and accessories driveshafts, and additionally the reduction gear assembly and propeller when the turbojet is employed as a turboprop. Figure 1, illustrating the lubrication system of the Pratt & Whitney Aircraft J-57, is a representative turbojet type.

The oil system is sealed from the combustion system, the oil supply being carried in an external tank or in one which is integral with, or mounted on, an engine casing. Normally, the pressure pump delivers its supply via a main filter, the oil to critical bearings and gears being directed through thread-type filters and metered orifices. Where loads are light and heat rejection is moderate, the splash system is used. Propeller oil supply in a turboprop is fed either from the main engine system or an auxiliary system using a different lubricant.

Oil is returned to the reservoir through an oil cooler by one or more scavenge pumps. Bearings which reject much heat require a high circulation rate and separate scavenge pumps. As it re-enters the oil tank, the oil is passed through a deaerator to separate most of the air from the scavenged oil.

OPERATING CONDITIONS — PISTON AND GAS TURBINE ENGINES

In a gas turbine, the air entering the intake is progressively heated in its passage through the compressor, the temperature rise in some of the higher output engines being as much as 600°F. The liberation of heat during combustion results in turbine inlet temperatures as high as 1600°F in some engines. Figure 2 illustrates the temperatures and main bearing locations in a typical twin spool turbojet engine. Part of the heat load is transferred to the bearings. For example, the normal operating temperature of the turbine bearing exceeds 500°F in many engines. When a gas turbine engine is rapidly shut down (thus stopping oil circulation), heat from the turbine discs causes a considerable rise in turbine bearing temperature, thus subjecting residual oil on the bearing to a high thermal stress.

In a piston engine, the oil is subjected to the severest conditions in the vicinity of the combustion chamber (Figure 3), Blow-by of combustion gases and high piston temperatures oxidize the oil and result in lacquer and carbon on the underside of the crown, on piston walls and in the piston ring grooves. In this area the oil must cool as well as lubricate. Similarly in the gas turbine engine the oil must cool and lubricate. However, a level of lacquer formation, which is normal in a piston engine, could not be tolerated on turbine and compressor bearings which have extremely fine tolerances.

The oil residence time is lower in a gas turbine than a piston engine. Comparable data for representative turboprop and piston types are:

Turboprop
—Flow rate 90 pints/min; tank capacity 32 pints

Piston engine
—Flow rate 376 pints/min; tank capacity 240 pints

It will thus be seen that the proportion of flow rate to tank capacity is 3:1 and 1.5:1 for the turboprop and piston engine, respectively.

While the oil in a gas turbine is principally subjected to thermal stress, oxidizing conditions are also present. These arise from the use of compressor bleed air at temperatures up to 600°F for sealing bearings. The resultant intimate mixing of hot air and oil introduces additional thermal stress and oxidation conditions on the lubricant.

OTHER LUBRICATION SYSTEM REQUIREMENTS

Apart from high temperature stability requirements, there are other important oil system conditions which must be met in a gas turbine engine lubricant.

Low temperature starting

Starting requirements down to −65°F call for oil viscosities that entail a minimum of viscous drag on bearings and gears and no pump cavitation. In view of the use of high oil circulation rates for cooling, it is also important that full flow is rapidly attained to critical bearings and gears. A maximum kinematic viscosity of 13,000 cs has been somewhat arbitrarily selected as a specification requirement for low temperature starting.

Load carrying ability

Although bearing loads are reasonably light in the turbojet, accessory drive loads may be quite high. The oil's load carrying ability becomes a critical requirement in the turboprop engine. Rotational speeds of up to 16,000 rpm necessitate a reduction gear ratio of more than 12:1 for the propeller in some engines. Gear sliding

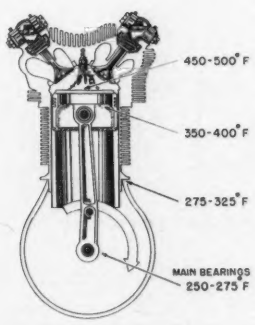


Figure 3
Piston engine temperatures

speeds are, therefore, high. Design changes to improve the power/weight ratio by decreasing gear size will result in still higher gear loads.

Low oil consumption

Since the gas turbine oil system is fully enclosed and is not subjected to the blow-by conditions that apply in a piston engine, oil consumption is principally a function of the efficiency of sealing devices. Comparable average realized consumption rates for typical piston and gas turbine engines are 3.5 gals/hr and 0.02 gals/hr, respectively.

Foam resistance

Exacting requirements are imposed on the deaeration devices in a gas turbine. These arise from the circulation of a relatively small quantity of oil at high velocity, the intimate mixing of air and oil at bearings and gears, and the high scavenging rate in bearing and gear compartments. The oil must, therefore, have good foam resistance, and any foam that forms must readily collapse.

Table 1 summarizes the operating conditions in the aircraft gas turbine.

TABLE 1
JET ENGINE OPERATING CONDITIONS

Flight Speed Range	Engine Type	Bearing Operating Range, °F.	Turbine Bearing Temp. (Soak Back) on Shut Down °F.	Bearing Loads	Gear Loads
Subsonic	Jet (Early)	−65 to 365	350	Light	Medium
Subsonic	Turbo-prop	−65 to 365	360	Light/ Medium	Heavy
Subsonic & Transsonic	Jet	−65 to 550	700	Light	Medium
Supersonic	Jet	−65 to 750	1,000	Light	Medium

LUBRICANT SELECTION

Mineral oil limitations

Temperatures were comparatively moderate in the old type turbine engines. Many of these are still in service and satisfactory operation is possible on low viscosity, low pour point mineral oils, such as MIL-0-6081B Grade 1010 (10 cs at 100°F). Similarly, mineral oils with a higher viscosity (80 cs at 100°F) than the Grade 1010 type have been and still are used for some of the early type turboprop engines. However, as power outputs increased, the resultant increase in bearing oil temperatures, gear and bearing unit loads indicated distinct shortcomings in the petroleum lubricants.

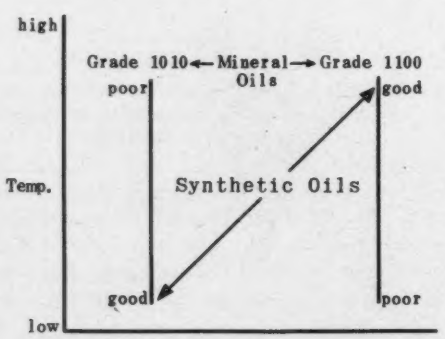


Figure 4
Synthetic oils — why?

Figure 4 shows that while Grade 1010 had good low temperature properties, its high temperature properties were poor. In fact, cases were encountered where high temperature evaporation loss of oil at high altitude was so great that the oil was exhausted before the mission was terminated by fuel supply. Furthermore, turbine bearing deposits became excessive because of poor oxidation stability.

The volatility characteristics imposed a distinct limitation in further increases of temperature and altitude when using a low viscosity lubricant of this type. Grade 1100 (270 cs at 100°F), on the other hand, had good high temperature properties in both lubricating qualities and volatility or evaporation loss characteristics. Unfortunately, its high viscosity at low temperature made it unsuitable in those applications where low temperature engine starting was a requirement. Obviously, what was required was a new lubricant which would combine the good low temperature properties of Grade 1010 with the good high temperature properties of Grade 1100. These are summarized in Table 2.

TABLE 2
QUALITY REQUIREMENTS OF AVIATION GAS TURBINE OILS

Performance Requirement	Desired Oil Property
Lubricate Heavily Loaded Gears and Gearings	45–100% of Load Carrying Ability of Grade 1100
Low Consumption	Low Evaporation Rate, Non-Foaming
	Compatible with Sealing Materials
Non-Corrosive	Thermally Stable }
Non-Deposit Forming	Oxidation Stable } at 350–450°F
	Non-Corrosive }
Low Temperature Pumpability	Viscosity at Min. Starting Temp. 5,000–20,000 cs.

DEVELOPMENT OF SYNTHETIC OIL

It became evident that, although the quality requirements could be individually met with different mineral oils, they could not all be achieved in one conventionally refined petroleum product. Development was, therefore, concentrated on a group of non-petroleum materials known as aliphatic esters. Esters are produced by reacting organic acids with alcohols, and it was known that di-esters (the chemical combination of two alcohol molecules with one dibasic acid molecule) possessed excellent lubricating properties combined with relatively low rates of viscosity change with temperature. In addition, some of these di-esters were pumpable at very low temperatures and had very low volatility compared with petroleum oils of similar viscosity. The limitations of these materials were inadequate viscosity at operating temperatures for satisfactory operation of propeller control governors and marginal load carrying abilities.

Co-operative research by petroleum chemists in the UK and USA led to the development of new types of complex esters of high molecular weight, relatively high viscosity and low pour point. They were found to have excellent load carrying properties, good thermal stability and, an important requirement, were mutually soluble in the selected di-esters in all proportions. It was thus possible to produce finished blends of esters of various viscosity levels, having load carrying properties well above those of piston engine lubricants, without the inclusion of chemical load carrying additives.

Although development in the UK and USA followed parallel paths, there were significant differences due to the different military requirements in the two countries. British policy attached great importance to high load carrying capacity and specified oil with a viscosity of 7.5 cs at 210°F; this ensured adequate bearing and gear lubrication while compromising the low temperature starting limit at –40°F. On the other hand, the American policy for jet engines stipulated satisfactory engine starting and functioning down to –65°F and limited kinematic oil viscosity to approximately 13,000 cs. A 210°F viscosity of 3.5 cs was considered appropriate, provided load carrying capacity was adequate.

The formulations which were finally found to most closely approach the desired performance characteristics of the USA and UK requirements are shown in Table 3. Current oils meet the military specifications which were developed and modified around these formulations.

TABLE 3
SYNTHETIC OIL TYPES

	US Type (MIL-L-7808)	UK Type (DEngRD 2487)
Kinematic Vis. @ 210°F, cs	3.6	7.7
@ 100°F, cs	14.0	37.2
@ –40°F, cs	1,830	11,677
@ –65°F, cs	12,400	80,000
Flash point, °F	460	470
Pour point, °F	–90	–70
Ryder gear load, lb/in	2,200	3,200

Table 4 summarizes the comparative characteristics of the two synthetic oils with the previously used petroleum base oils, and clearly indicates the extent to which the basic objectives were achieved.

TABLE 4
SYNTHETIC AND MINERAL OILS—COMPARISON

	Grade 1010 (Mineral)	US Synthetic Type (MIL-L-7808)	UK Synthetic Type (DEngRD 2487)	Grade 1100 (Mineral)
Kinematic Vis. @ 210°F, cs	2.46	3.6	7.7	20.4
@ 100°F, cs	10.1	14.0	37.2	244
@ 0°F, cs	212	230	1,000	30,600
@ –40°F, cs	2,442	1,830	11,677	–
@ –65°F, cs	20,300	12,400	80,000	–
Flash point, °F	295	460	470	490
Pour point, °F	–80	–90	–70	0
Ryder gear load lb/in	700	2,200	3,200	2,700

LABORATORY PERFORMANCE TESTS

The final criterion in evaluating an oil is its performance in an actual engine. The high cost of engine tests makes it necessary to screen oils under laboratory conditions which are sufficiently reliable to predict performance in an actual engine.

During the early development of synthetic oil, it was found that the familiar laboratory tests for screening petroleum lubricants were totally inadequate for this new type of lubricant. Numerous tests have, therefore, been developed by petroleum companies and the principal engine manufacturers for assessing the critical characteristics of the oil. A few of the most significant are the thermal stability, corrosion/oxidation and IAE gear tests specified in the British specification, and the Panel Coker, Deposition and Ryder gear tests developed in the USA. Bearing tests have been evolved in both countries.

OPERATIONAL EXPERIENCE

Historical

Following an extensive bench evaluation program, late in 1951 Rolls-Royce embarked on an active flight test program of synthetic oil in a Dakota aircraft powered by Dart turboprop engines. This engine manufacturer extended this program in 1952 to include the Derwent, Nene and Avon engines. A co-operative program with British European Airways in this airline's own Dakota/Dart indicated that low temperature starting could be lowered from 5°F on mineral oil to below –13°F with synthetic oil.

By the winter of 1953-54, British European Airways had standardized on this oil, and the necessity for using a lubricant suitable for year-round operation resulted in exclusive Rolls-Royce approval of synthetic oil for the Dart in 1954.

In the meantime, a parallel evaluation program was being undertaken in military aircraft. Apart from some earlier engines operating at a level still permitting the use of mineral oil, by 1954 most military gas turbines in the UK were using synthetic oil.

The USA development of synthetic oil stemmed from a requirement which originated with Pratt & Whitney Aircraft around 1950, the UK experience being found invaluable in accelerating the USA approach. Synthetic oil was specified when the Pratt & Whitney Aircraft J-57 turbojet entered military service in 1951. The civil version of this engine, the JT-3, commenced its civil life with Pan American's introduction of the first Boeing 707 into commercial airline transportation in December 1958. All development testing of the Allison 501 turboprop was carried out on synthetic oil. This engine entered commercial operations in the Lockheed Electra in 1958. Since 1950, all high output US gas turbines have been developed on synthetic oil and, with the exception of a few older types, all military engines are now using synthetic oil.

GENERAL PERFORMANCE AND ASSESSMENT

The extensive civil and military operating experience in a variety of engine types on synthetic oil since 1953 has been remarkable for the absence of problems associated with the lubricant itself.

Experience to date in evaluating oil performance in gas turbine engines has indicated the necessity for developing new concepts compared with those hitherto used for piston engines. Deposit levels in gas turbine engines are substantially lower than in piston engines. Carbon does not usually exceed a smooth dull or satin layer in the hottest bearing zones. Localized hot areas, where deposits will be higher, vary with engine type. Cool operating locations are normally clean, but thin layers of soft sludge tend to be centrifuged in the bores of parts rotating at high rpm and where oil mist is present.

Deposits in turbine engines thus entail a more critical assessment and greater accuracy in assigning demerit ratings. Close differentiation is also necessary between types of deposits, since some are much more undesirable

than others in a jet engine. Colour photography has been found particularly effective for illustrating the low deposits and interpreting the demerit ratings in oil performance reports.

Due to the limited engine rating experience, it has not yet been determined if the mechanical performance of a synthetic oil can be assessed by visual inspection. Invariably, wear is so negligible that it is not readily discernible, final grinding marks on items such as reduction gears being frequently present after operating 5,000 hours or more. Engine manufacturers naturally adopt a cautious policy to reinstalling at overhaul parts which have been found critical. Such items may thus be life restricted, although visually and dimensionally serviceable.

These considerations point to the necessity for developing new rating techniques for evaluating surface condition as a yardstick of the mechanical performance of an oil in a gas turbine.

ENGINE TYPES

It is not possible in this paper to cover the experience of synthetic oil in all engine types, but the following summaries are representative of the engines in commercial service.

Rolls-Royce Dart

Since the introduction of the Vickers Viscount into commercial airline service in 1952, over 9 million engine hours had been accumulated on synthetic oil between August 1953 and December 1959. All of this experience has been obtained on a single synthetic oil formulation; either a UK product meeting DEngRD2487 or its American equivalent. During this period, the overhaul life has been gradually extended to 2,500 hours from the initial 400 hours, with flight trials under way for further extensions. This is a noteworthy achievement when compared with the increase in overhaul life to 1,800/2,000 hours after sixteen years' service of the Pratt & Whitney Aircraft R-2800 – one of the most reliable piston engines still actively operated.

The Dart is a moderate temperature engine, is not lubricant limited even at 2,500 hours and there are no oil drains during this period. The latest published oil consumption rate for all engines in service is 0.06 pints/engine/hour. Deposits are low throughout the engine, those on the hottest bearings (rear compressor and turbine) varying from a thin brown varnish to a dull or shiny black lacquer. Thin layers of soft sludge are usually found in the bores of the main rotor shafts and some reduction gears. The accessory drives, reduction gears (bores excepted) and their casings are clean, but some Viscount operators have experienced sludging of the propeller governors.

Normally, wear cannot be readily detected by visual inspection and component replacements for wear alone are relatively low. A typical replacement factor for reduction gear layshafts – one of the most heavily loaded gears in the engine – is 0.0016 per 1,000 hours. This was achieved in 1958 by TCA, an operator of a fleet of fifty Viscounts.

Bristol Proteus

Up to the end of 1959, the Bristol Proteus 750/761 series engines in Britannia aircraft had operated nearly 500,000 hours on DEngRD2487 synthetic oil. The overhaul life has been increased from 700 hours to 1,250 hours and trials are in progress with BOAC to extend this life to 1,700 hours. The oil is not drained, and the normal oil consumption is approximately 1-1.5 pints/engine/hour.

The hottest bearing is the rear turbine and, on soak back, the outer race attains a temperature of approximately 482°F, the normal operating temperature being 392°F maximum. Light dull black carbon deposits occur at this location. Other compressor and turbine bearing deposits vary from a stain to a light or dark brown varnish. Soft sludge is centrifuged at some locations. Reduction and accessory drive gears and housings are clean.

The teeth of the double helical reduction gears are exceptional for the absence of wear. It is interesting to record that one airline undertook a flight trial of a mineral oil (9 cs at 210°F) in the 755 series engine. The operator felt a mineral oil should be satisfactory since the routes were not in low temperature operating areas. Following a number of compressor bearing failures, the trial was discontinued. Since reverting to synthetic oil, bearing serviceability is again satisfactory.

Pratt & Whitney Aircraft JT-3 and JT-4

The Pratt & Whitney Aircraft JT-3 and its military equivalent, the J-57, had accumulated over 6 million engine hours on low viscosity oil up to December 1959. To date, no mechanical problems have been associated with lubricant deficiencies. On the JT-3, turbine and compressor bearing deposits at 800 hours are usually a tan stain or thin black varnish. Deposits on bearing housings range from a light varnish to a small amount of carbon on the upper sections of the housings. Carbon forms in the retainer grooves of the carbon oil seals, and a small degree of seal wear occasionally occurs. Coking was noticeable in hot spots of early engines, but has been alleviated by oil system modifications. Bearings are replaced on condition, and the low average replacement factor of 0.4 main bearings per thousand engine hours indicates excellent serviceability.

The average oil consumption is 0.16 pints/engine/hour. The initial oil drain period for the JT-3 and JT-4 engines is 150 hours, but some operators have received P & W A's approval to extend this to 250 and 300 hours for the JT-3 and JT-4 respectively. The higher drain figure for the JT-4 reflects a lower level of oil stress probably as a result of oil system modifications and a higher capacity oil system.

Allison 501

The Allison 501 turboprop entered airline service in the Lockheed Electra in November 1958, and on December 1, 1959, the running time exceeded 500,000 engine hours. Synthetic oil of 7.5 cs at 210°F is the only lubricant approved for this engine.

Deposits on the main rotor bearings vary from a light to dark brown varnish. Some carbonaceous deposits occur on the front turbine bearing support housing and

modifications have been introduced to correct this condition. The reduction gears and housing are clean. The overhaul life has recently been extended from 800 to 1,000 hours, the average oil consumption is 0.15 pints/engine/hour and the oil is drained at 300 hour intervals.

ECONOMICS AND RECLAIMING

The cost of the materials used in ester type synthetic oils is considerably greater than conventional mineral oil formulations. However, the resultant higher price per gallon is offset by the low oil consumption of the gas turbine. Using the DC-8 or Boeing 707 and average US oil costs as a basis for comparison, it can be shown that the total hourly consumption per aircraft can be as low as one pint. This is equivalent to a total cost of approximately 65c per hour or 0.09% of the direct operating cost, based on present oil costs. It is also interesting to note that a differential of $1.00 per gallon in oil price will result in a difference in operating cost of approximately 12½c/aircraft/hour. These comparative data assume an average consumption of 0.25 pint/hour for each engine – a realistic figure based on operating experience.

During 1953, investigations showed the possibilities of reclaiming the synthetic oil then in use in the Rolls-Royce Dart. The economic benefits of reclaiming were recognized by British European Airways in 1954 and this prompted further work.

It was found that very little deterioration of this oil occurred in this engine. Reclaiming was proved to be a practical and economical procedure provided the oil had not been contaminated by mineral oil, grease, hydraulic fluid or other extraneous material.

If the viscosity/temperature characteristics have not been impaired, experience to date has shown that reduction in insoluble matter by efficient filtration will restore this oil to its original condition. Vacuum steam distillation is effective in removing water and kerosene where gross contamination with these materials has occurred. No economic procedure exists for removing mineral oil and grease. Table 5 illustrates the effect of contaminating this particular synthetic oil with a light grade mineral oil. Note that low temperature viscosity readily detects even 1% contamination.

TABLE 5
EFFECT OF LIGHT GRADE MINERAL OIL CONTAMINATION ON DEngRD—2487 TYPE SYNTHETIC OIL

Inspection	Percentage contamination by mineral oil			
	None	1%	5%	10%
Kinematic Vis. @ 210°F, cs	7.79	7.72	7.71	7.72
" " @ 100°F, cs	37.4	37.1	37.3	37.6
" " @ −40°F, cs	11,900	12,500	29,700	Almost Solid

Since the successful completion of flight trials on this reclaimed oil by TCA and BEA in 1957, reclamation has been adopted by many Viscount operators. Rolls-Royce has issued a controlling specification for the procedure. BOAC also operates with reclaimed oil in the Rolls-Royce Avon RA-29 engines of the Comet IV. Napier use it for testing Eland and Gazelle engines.

Reclaiming of this oil after use in the Proteus 755 turboprop engine was approved by Bristol Aero Engines in 1957. Some Britannia operators are now following a similar procedure to that established for the Viscount.

The RAF has also successfully used this oil after reclaiming. Proving flights in Avon Canberras and Sapphire Hunters in 1959 lead to the issue of DEngRD-2493. This specification covers service reclamation and differs only in minor details from the Rolls-Royce specification.

Following the success achieved in reclaiming used oil from Dart and Proteus engines, the feasibility has been investigated of adopting a similar procedure for the lower viscosity oil used in Pratt & Whitney Aircraft JT-3 engines in Boeing 707 aircraft. Laboratory analysis of samples drained at 150 hour intervals has indicated chemical deterioration beyond the point of economical reclamation. Degradation has been manifested as an increase in the acidity and is indicative of thermal stressing of the oil in this engine. However, inspection of a representative number of airline engines at overhaul revealed no indications of abnormal wear or corrosion with this level of oil deterioration, bearings, gears, seals and other critical parts in contact with the oil showing no signs of lubricant induced problems. This excellent engine condition has made it possible to extend oil drain periods which is equivalent to some measure of reclamation.

While complete studies have not yet been made, it would appear that used oil from Allison 501 engines also degrades beyond the point of economic reclamation.

It will thus be realized that, excluding contamination factors, the feasibility of reclaming synthetic oil is directly related to the thermal stress the lubricant is subjected to. Since this will vary in different engines, reclaiming must be assessed on each engine type.

EFFECTS OF SYNTHETIC OIL ON MATERIALS

The advent of synthetic oil for aircraft gas turbine lubrication brought with it problems of compatibility for metals, elastomers, paints, varnishes, insulation materials and plastics. All materials associated with synthetic lubricants in aircraft have been reviewed and many new types evolved.

Metals

At sustained high oil temperatures, copper exerts a somewhat greater catalytic effect on organic-ester base lubricants than other metals. As a result, the esters tend to break down to acid derivations. However, high copper alloys such as brass and bronze have not proved impractical in current engines.

Steel, aluminium and their alloys, magnesium alloys, tin, monel, and inconel are compatible.

Hard chrome and nickel plating are satisfactory. At high temperatures cadmium has a tendency to be taken into solution. While this solvent action may not impair the lubricant, the gradual removal of cadmium will adversely affect its anti-corrosive properties. Zinc as a galvanizing protective is attacked by synthetic lubricants leading to the formation of zinc soaps. Babbitt tin-base alloys, white metals and indium flashed copper have been found satisfactory as bearing materials. Storage is best

TABLE 6
EFFECTS OF SYNTHETIC OIL ON METALS

Satisfactory	Marginal	Not compatible
Steel & Alloys Aluminium & Alloys Copper/Aluminium Alloys Magnesium Monel, Inconel, White Metals (Tin Base) Chrome Plating Nickel Plating Tin Plating Indium Flashed Copper	Copper Brass & Copper Alloys Tungum Cadmium Plating	Lead Base Bearings Zinc Plating

TABLE 7
EFFECTS OF SYNTHETIC OIL ON ELASTOMERS, PAINTS, VARNISHES AND PLASTICS

Satisfactory	Marginal	Not compatible
Silicone Rubber Acrylo-Nitrile Rubber Teflon, Nylon Poly Esters, Tufnol Phenolic/Formaldehydes Perspex Alkyd Varnish Epoxy Resin	Buna-s Phenolic Varnish	Neoprene Natural Rubber Butyl Polyethylene P.V.C.

achieved in tinned mild steel cans or bright mild steel drums. Aluminium alloy or stainless steel are recommended for aircraft oil tanks.

Elastomers

Contrary to experience with mineral oils, neoprene type rubbers are unsuitable due to high swell, with high nitrile, silicone, medium nitrile and butyl being the preferred types in that order of preference. One disadvantage of the silicone rubbers is a mechanical strength less than half that of nitrile rubber.

Paints and varnishes

The epoxy resin base paints have been found to be practically the only compatible type. Except in very light shades, there is no breakdown, softening or staining through contact with synthetic oils.

Many commonly used phenolic impregnated varnishes are softened by contact with the hot oil, but a few of the harder grades show moderate to good resistance.

Plastics

Teflon has been found to be the most satisfactory with the high molecular weight nylon a close second. At locations where aircraft wiring might be subject to spillage of synthetic oil, nylon or nylon doped insulation should be used.

Tables 6 and 7 summarize the material experience with synthetic oils.

IMMEDIATE AND FUTURE REQUIREMENTS

Although synthetic oil development has hitherto kept pace with engine development, the currently available synthetic oils are becoming marginal as existing engines are uprated and thrusts increase. It is obvious that the higher airspeeds and operating temperatures will demand lubricants with vastly improved properties compared with those now available.

Immediate

It would appear that existing 7.5 cs synthetic oils should be adequate for the turboprops now in service, and those which are due to commence their service life in the immediate future. On the other hand, current 3 cs (MIL-L-7808) oils are being thermally stressed to their upper limits in some of the engines now in service, particularly those in supersonic military aircraft. Similar conditions will apply when existing civil types are fully developed. Bulk oil temperatures may significantly increase in the front fan turbojet engine due to less heat dissipation as a result of the insulating effect of the secondary airstream. Currently available commercial turbojet oils are thought to be marginal under continuous running conditions at bulk oil temperatures of 250°F, or at the short operating periods at Mach 1-plus air speeds. A 20-30°F improvement is immediately desirable in present 3 cs viscosity lubricants.

Future

The temperatures of the future series of turbojets will require new lubricants. The problems arising from higher engine temperatures will be accentuated by the aerodynamic heating effects of aircraft travelling at

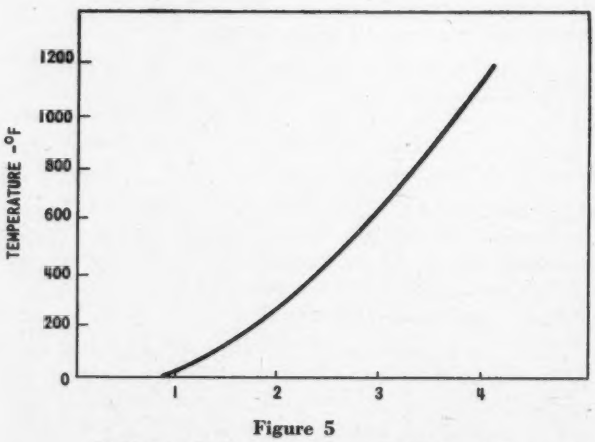


Figure 5
Mach number — ram air temperature rise

M 2-3 air speeds. Figure 5 illustrates the ram air temperature rise–Mach number relationship. It will be noted that an increase in ram air temperature of 400°F will occur at *M* 2.4. This will approximately correspond with the bulk oil temperature which is specified as a target limit in MIL-L-9236, a specification evolved to meet the lubricant demands of future aircraft gas turbine engines. Table 8 is a comparison of present and the anticipated future temperatures based on present trends.

Synthetic lubricants such as polyphenyl ethers and super-refined mineral oils are candidates for future application. The objection to these materials is that low temperature properties may have to be sacrificed in order to attain the high temperature requirements.

TABLE 8
JET ENGINE TEMPERATURES—PRESENT AND FUTURE

	Present	Future
Bulk Oil °F	250	600+
Hot spots, °F	800	1000+
Bearings, °F	350–500	800+
Gears, °F	250	600+
Heat rejection Rate, Btu/Min	3000	7000+

In the case of turboprop engines, while future types may still be satisfied by the load carrying capacity of the present synthetic oils, temperature trends will require oils with improved oxidation and thermal stability properties.

The predicted temperatures for future turbojets pose a challenge to petroleum chemists. The answer to this may be a combination of improved oils and a radical approach to lubricant system design.

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NATIONAL AVIATION MUSEUM

There is in the advanced construction stage in Ottawa a National Aviation Museum. Is should be open to the public late in the spring of this year.

This Museum has evolved under the auspices of the National Research Council Associate Committee on a National Aviation Museum.

Donations and assistance from industry and from individuals have made possible the commencement of this Museum in adequate space made available in the new Air Terminal Building at Uplands by the Minister of Transport.

The Government has now formally established this Aviation Museum as a first step towards a National Science Museum, and it will thus open under the direction of the Department of Northern Affairs and National Resources, as a permanent organization.

Starting with the nucleus of historic items available, a significant collection has already been arranged for display; but there are many more documents, maps, photographs and other historic items of hardware which may be lost. If they are presented to the Museum, they will be preserved and acknowledgment made of the donation. It is only in this way that the collection can be built up. It would be appreciated if those who have or know of display material could advise us.

Shortly, a Curator and staff will be appointed to continue the work. Make no mistake, a Museum must continue to evolve and develop. It may not remain static or it will cease to exist. In this work it will need the continuing assistance which has so willingly been given to me, and for which I am most grateful, as Interim Curator during the formative period.

M. S. Kuhring
Interim Curator

RECENT ADVANCES IN BALL AND ROLLER BEARINGS†

by T. H. Cooper*

Canadian SKF Company Limited

SUMMARY

Ball and roller bearings, or rolling element bearings, were originally brought into being during the latter half of the nineteenth century; the industry was well established at the conclusion of World War I, and matured during the next twenty years.

The impact of World War II and its mass production of reciprocating aircraft powerplants placed new demands on the rolling element bearing, but these were to be exceeded in the post-war years by the advent of the gas turbine. Some of the main problems presented to rolling element bearing metallurgists and designers, and their solutions, are presented.

EARLY HISTORY

THE history of ball and roller bearings can probably be stated to have commenced at about the same time as the invention of the wheel. It was at that time that early mankind found that considerably less effort was required to move a heavy object if it was placed on a quantity of roughly cylindrical shaped objects and pulled in that fashion, rather than dragging it over the ground. The reason for this lessening of the required tractive effort was, of course, because the friction was reduced to a marked degree by the substitution of rolling motion for sliding motion. You will also appreciate the fact that this principle is the basic principle of the ball and roller bearings of today and, although they are generally referred to, in order to distinguish them from plain, bronze or sliding bearings, as anti-friction bearings, the term "rolling element bearings" is also, if less frequently, used and at the same time is possibly a more descriptive appellation.

However rolling element bearings, as we know them today, did not really come into their own until during the latter half of the nineteenth century when bicycles came to be used in large quantities as personal transportation. It was soon found that considerably less effort was required on the part of the rider if the wheel and pedal bearings were of the rolling type. To meet this requirement, steel balls were used to run between separate cup and cone races, very little different (in design) from those used in bicycles today.

With the development of the steel ball industry, it was not a long step from there to the design and development of self-contained ball bearings as we know them today and by the beginning of the twentieth century there were several factories in Europe and the USA manufacturing ball and roller bearings. In 1907, to meet the requirements for a bearing that could handle some degree of misalignment, the self-aligning (or spherical) ball bearing was developed and, following along these lines, the self-aligning spherical roller bearing was developed shortly after World War I.

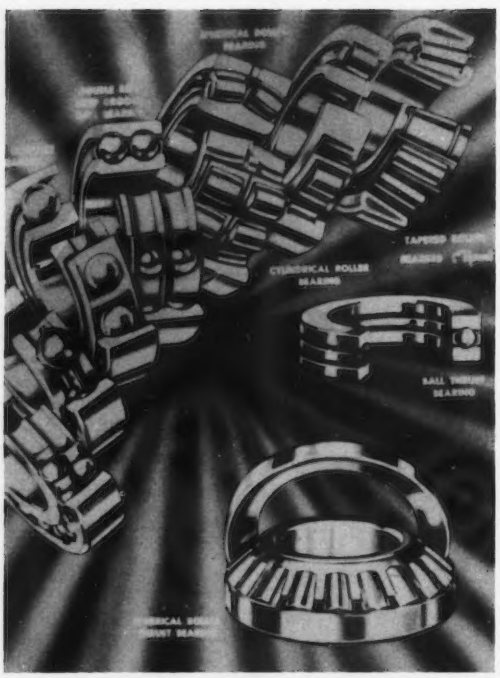


Figure 1
Basic types of rolling element bearings

BASIC TYPES (Figure 1)

A brief description of each type might be in order here.

The most common type is the single row, deep groove, ball bearing which has good carrying capacity in both radial and thrust directions, is relatively simple and cheap to manufacture and will tolerate small amounts of misalignment between shaft and housing. For increased radial carrying capacity, one derivative of this type is the so-called maximum type bearing, which has more balls than the basic type but cannot carry any appre-

†Paper read at the Mid-season Meeting of the C.A.I. in Edmonton on the 20th February, 1960.

*Assistant Chief Engineer

ciable thrust load due to the filling notches which are required to be able to insert the additional balls. For maximum thrust carrying capacity, the angular contact ball bearing is used, but, unless it is used opposed against another one, this type must run under a constantly applied thrust load. The double row self-aligning ball bearing will permit shaft misalignments up to 3° but, since the outer ring raceway is a sphere and not a deep groove, the carrying capacity is not as great as the single row deep groove type. The double row angular contact ball bearing permits shaft location by one bearing with no axial displacement.

The cylindrical roller bearing has the advantage that it has line, rather than point, contact between rolling elements and races, and this produces lower unit stresses in the material and, hence, greater carrying capacity. It is unable to tolerate any misalignment however, and is not capable of carrying any thrust load, with one exception. This exception, which utilizes a guiding flange (or flanges), involves sliding motion rather than rolling motion, and therefore the thrust carrying capacity is very small. The tapered roller bearing however, used in opposed pairs, can carry heavy radial or thrust loads, or combinations of both, with the thrust carrying capacity dependent on the angle of the taper. The double row self-aligning spherical roller bearing, which has the roller bearing's inherent load carrying capacity, can carry thrust load from either direction and can tolerate misalignments of up to 2°, whereas all the other types of roller bearings are very sensitive to misalignment. When the roller length in a cylindrical roller bearing exceeds by about 3 times its diameter it becomes known as a needle roller bearing, which has a very thin section and can be used in applications where radial space is very limited.

The other type of rolling bearing is the thrust bearing, either ball or roller, which is designed for thrust carrying capacity only. The self-aligning spherical roller thrust bearing is the only one of this type that will permit some misalignment and also carry a small radial load in conjunction with a predominant thrust load.

WORLD WAR II

Although all the above types (except the spherical roller thrust bearing) were in general use several years prior to the commencement of World War II, it soon became apparent that there were only two or three of these types that were suitable for use in the reciprocating engine aircraft powerplants that were built in such great quantities during the war. Although there were many applications where plain, sleeve type, bearings were used, the rolling bearings used were for the most part of the single row, deep groove, ball bearing type and its derivation, the angular contact ball bearing (used singly or in duplex pairs), and cylindrical roller bearings.

The main reason why these three types were used to the almost complete exclusion of the others in the reciprocating engines is that they are the only ones capable of carrying relatively heavy loads combined with the relatively high speeds involved. As a general rule, it can be stated that it was the speed of the application that dictated the use of these three types to the virtual exclusion of all the others.

The range of applications for these bearings extended all the way down from main crankshaft bearings to supercharger and gear-box bearings to rocker arm bearings, and even to the synchronizer drive that enabled the pilot of the early single-engine fighters to fire his machine gun through the propeller without shooting himself out of the air.

THE GAS TURBINE AGE

By the end of the war in 1945, piston engine development had, except for one or two large engines, come to a halt, and the gas turbine age had already commenced. The problems presented by this new propulsion unit to the anti-friction bearing designer were at the same time both similar to and different from those which had been presented by the reciprocating engine. They were similar to the extent that most of the problems previously faced were still there, and they were different in that a host of new ones were presented. The only ones which were disposed of were the centrifugal force loads of the crankshaft and the oscillatory motion of the rocker arm and other reciprocating parts.

Effects of the gas turbine

As previously mentioned the gas turbine age commenced prior to the end of the World War II and, with the advent of the Korean War in 1950, design and development proceeded with great urgency, and has continued to do so since that time, although the main emphasis may now be shifting from the military to the commercial sphere. How has the development of this propulsion unit affected the anti-friction bearing industry? Let us examine the basic elements of the bearing individually, starting with the material for the rolling elements and races.

Materials

Since their original development at the turn of the century, bearing races and rolling elements have either been manufactured from a through-hardening carbon-chrome steel of the SAE 52100 type or a carburizing nickel alloy steel. The former is the more common to the aviation powerplant industry and it is therefore proposed to discuss this type only.

Since SAE 52100 has been in use for so long, there has not been too much room for its further development. This material has very good hardness and fatigue resistance properties when operated at temperatures up to 350°F. Since this temperature is higher than petroleum base lubricating oils are capable of withstanding, there was initially no demand for a material suitable for operating at temperatures much higher than 250°F. However it was not long before conditions demanded the development of synthetic lubricants capable of withstanding higher bulk temperatures, and these were developed principally according to the US specification MIL-L-7808. With the development of these oils, bearing designers and metallurgists had to search for materials that could extend the good fatigue and hardness properties of 52100 steel up to the new range of temperatures that were to be encountered. Some of these requirements are listed in Table 1.

TABLE 1
REQUIREMENTS FOR A HIGH TEMPERATURE MATERIAL

(1) An analysis which could be heat treated to obtain an acceptable hardness and yet maintain dimensional stability at maximum operating temperature.
(2) For ultimate load carrying capacity, a minimum hardness of at least Rockwell C-58 at the operating temperature.
(3) Tungsten content should be held to a minimum, because it could be in short supply.
(4) Machining, hardenability and grinding characteristics should be as close as possible to 52100.

To meet these requirements several analyses, listed in Table 2 compared with 52100, were investigated by our company.

TABLE 2
STEEL ANALYSES CONSIDERED FOR HIGH TEMPERATURE BEARINGS

Material	C	Mn	Si	Cr	P	S	Ni	Cu	Mo	W	V
52100	1.00	0.35	0.30	1.45	0.025	0.025	0.35	0.25	0.08	–	–
MHT	1.00	0.35	0.40	1.45	0.025	0.025	0.35	0.25	0.08	(1.00 Al)	
M 1	0.80	0.30	0.30	3.90	0.030	0.030	–	–	8.90	1.55	1.00
M 2	0.80	0.30	0.30	4.17	0.030	0.030	–	–	5.00	6.00	2.00
M 10	0.90	0.25	0.30	4.10	0.030	0.030	–	–	8.10	1.00	2.00
M 50	0.80	0.35	0.25	4.00	0.015	0.015	0.010	0.010	4.25	0.25	1.00
T 1(18-4-1)	0.70	0.30	0.30	4.17			–		–	18.00	1.10

The hot hardness figures for these steels are shown in Figure 2.

It will be seen from these tables that the analysis most closely approaching 52100 is MHT and this was the first substitute material to be used. Since its hot hardness is only very slightly better than 52100 however, it did not really provide an answer to the problem. 18-4-1 is the material used by the British for high temperature bearings, and was introduced to this continent when a British turbine was to be manufactured in the USA under licence. However this analysis, with 18% tungsten, certainly did not meet requirement No. 3 of Table 1 and, therefore, it has not been used here. M 2 was also rejected on this account.

M 10 was found to produce reasonably satisfactory bearings, but the grindability was so poor that it was doubtful that the capacity of the entire bearing industry would be sufficient to meet the demands of a military emergency. We have found through experimentation that the grindability of the M steels compared with 52100 are as shown in Table 3.

TABLE 3
GRINDABILITY OF VARIOUS TOOL STEELS AS COMPARED WITH 52100

52100	1.0
M 1 & M 50	1.8
M 2	3.0
M 10	4.0

Considering all the above facts, we are now making the recommendation shown in Table 4.

TABLE 4
OPERATING TEMPERATURE LIMITS FOR DIFFERENT STEELS

52100 up to 350°F
M 50 „ „ 600°F
M 1 „ „ 800°F

Bearing fatigue

While we are discussing materials, a few words on the subject of fatigue would be in order. All rolling element bearings, or any given point in them, are subjected to repeated stress cycles as each rolling element passes over the given point. This constant repetitive stress, which is a direct function of the number of revolutions the bearing has turned, eventually produces sub-surface cracks and then flaking of the surface material. Being what it is, the actual fatigue life of one particular bearing is not generally the same as an apparently identical bearing loaded under identical conditions. Bearing this in mind, the Anti-Friction Bearing Manufacturers' Association, the American Standards Association and the International Standards Organization have all agreed that the rating life of a group of apparently identical bearings is the number of revolutions that 90% of a group of bearings will complete or exceed before the first evidence of fatigue develops.

Comparison of the fatigue properties of various materials can be readily evaluated, since there is a standardized formula for determining the basic load rating (C) of a ball bearing. The formula is

$$C = f_c (i \cos \alpha)^{0.7} Z^{2/3} D^{1.8} \qquad (1)$$

where i = the number of rows per bearing
α = nominal contact angle
Z = the number of balls per row
D = the ball diameter
f_c = a factor which depends on the geometry of the bearing components.

(The basic load rating of a ball bearing is defined as the equivalent radial load a bearing can endure for a rating life of one million revolutions.)

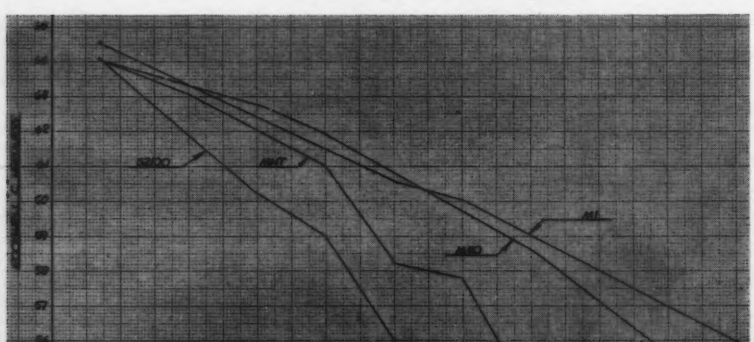


Figure 2
Hot hardness values for light temperature bearing steels

Vacuum melting

A further development in rolling bearing materials has been the introduction of vacuum melting. Basic electric arc melting has been the source of most of the 52100 material used, but since the M tool steels inherently contain more inclusions of a nature likely to reduce fatigue resistance, the vacuum melting method currently offers the most promise of a method to increase the cleanliness of these materials.

Original vacuum melted steels were produced by the induction method. This requires that the charge be melted in a refractory lined crucible and poured over a refractory spout into a substantially conventional ingot mould coated with a refractory mould wash (Figure 3). As a result, induction vacuum melted heats, and finished parts made from such heats, have shown more non-metallic inclusion of rather larger sizes than is desirable.

A more recently introduced method is the consumable electrode process, in which an electrode of the material in question is progressively melted under vacuum by the heat of an electric arc and the ingot is built up continuously in a water-cooled copper mould. Therefore, no exogenous non-metallics are added, and considerable quantities of the non-metallics in the electrodes are eliminated by disassociation and by cropping. Those not eliminated are broken up into a very fine dispersion.

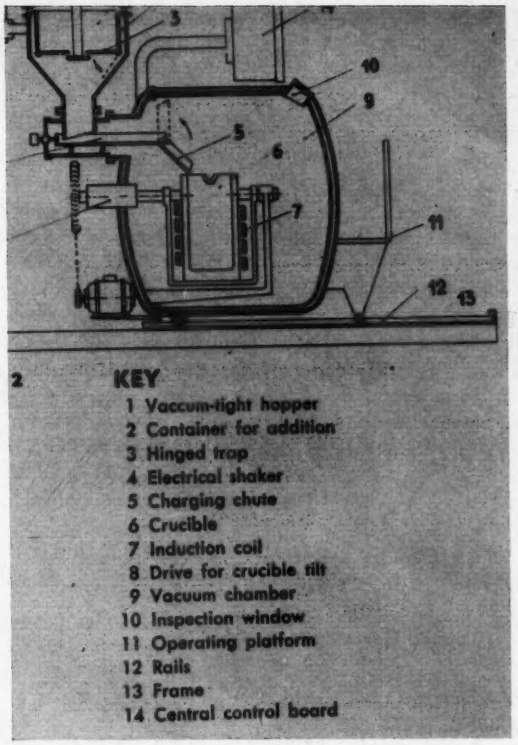


Figure 3
Principle of induction vacuum melting

Life tests

Life tests, based on the principles mentioned above, are still going on, but so far the following results have been evaluated:

(1) Vacuum melted 52100 steels produce bearings with slightly greater lives than conventional melts, but whether the additional cost is warranted is still debatable.

(2) There is no indication that vacuum melting reduces the number of early failures, that is those occurring before 10% of the estimated life.

(3) Vacuum melted tool steels (M 1 and M 50) do have longer life than conventional melt tool steels.

(4) Vacuum melted tool steels (M 1 and M 50) also have longer life than conventional melt 52100 when tested under the same conditions at room temperature.

(5) The lives of vacuum melted tool steel (M 1 and M 50) bearings are less at elevated temperatures (450°F) than at room temperature. This is apparently due to the fact that the synthetic oil which has to be used at the higher temperature definitely has a deleterious effect on bearing life as compared with petroleum base lubricant.

Cages

So much for the race and rolling element materials. How has the development of the gas turbine affected the bearing cage, or separator, which separates the rolling elements from one another? Whether the cage is centered either on the rolling elements or on the rings themselves, the motion involved is sliding rather than rolling, and therefore speed is a very important factor. When speaking of a rolling element bearing's speed factor we usually use the term "*dn*" in the aircraft bearing field. This is the bore in millimetres (*d*) multiplied by the rpm (*n*) and prior to the introduction of the gas turbine *dn* values in excess of 0.3×10^6 were rare. Figures of 1.0×10^6 are now quite common, however, and 2.0 and even 3.0×10^6 are appearing.

The standard cage for ball bearings has been and still is of pressed steel ribbon type design, centered on the balls (Figure 4). Where these were not satisfactory in reciprocating engine use, ring centered machined cages of centrifugally cast brass or aluminum or phenolic material were used with great success. Of these, only the last named material is suitable for very high speeds, but on the other hand it is restricted to a maximum operating temperature of 250°F, and therefore a new cage material, silicon iron bronze, first used in England, has become the standard cage material for gas turbine engines. This material is of the analysis shown in Table 5 and is satisfactory for use up to at least 600°F. It is also a fairly hard material and, to reduce friction between cages and the races, balls or rollers, it is usually silver plated (or silver-lead plated) especially when there is the possibility of dry starts due to soak back of heat from the hot parts of the engine after shut down. It should also be mentioned that it was fairly common piston

TABLE 5
SILICON IRON BRONZE ANALYSIS

Si	Fe	Zn	Mn	P	Cu
3.25	1.50	2.75	1.00	0.10	Remainder

engine practice to apply phosphate or black oxide coatings to the rings for protection against corrosion and the better retention of an oil film, but this practice has not been used in new applications in the last few years.

Design

And now how has the development of the gas turbine altered the design of ball and roller bearings? The requirements that have to be met are (a) high speeds and (b) high loads. High temperatures have already been discussed.

The effect of the former is principally on the cage, which has also been partially discussed. Ball and roller centered cages are only satisfactory for low *dn* values, and ring centered cages have become mandatory in most gas turbine applications. These require carefully chosen clearances (and close manufacturing limits) between the cages and ring surfaces so that they are neither too large to reduce the area in contact (which would accelerate wear) nor too small to prevent differential thermal expansion of the two members.

Apart from the improved cage the only other principal requirement to operate ball and cylindrical roller

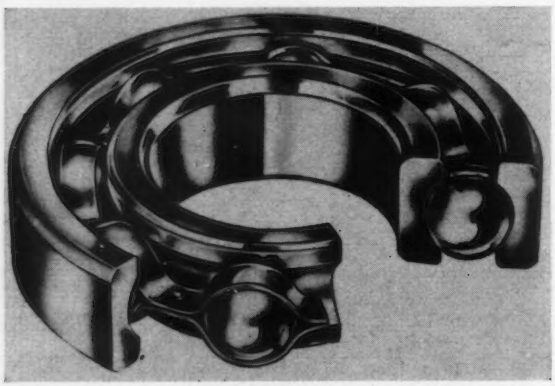


Figure 4
Standard deep groove ball bearing with ball centred pressed steel separators

bearings at high *dn* values is improved lubrication, but this should really be considered as part of the application and not the bearing.

As will be seen from the formula for calculating the basic load rating of a bearing (Eq. 1), this can be increased by increasing the size and/or quantity of the rolling elements.

Since the mainshaft ball thrust bearing is generally very heavily loaded, the problem of how to combine into one bearing the full complement thrust capacity of an angular contact bearing with the bi-directional thrust capacity of the Conrad type, deep groove, bearing has been solved by the development of the split inner ring bearing (Figure 5). This type of bearing was originally developed to meet the needs of reversible pitch propellers, but it is now used on virtually all gas turbines. It has also simplified cage design, since these can now be one piece construction instead of two halves riveted together.

In roller bearings the development of the crowned roller has been an important feature. As shown in Figure 6, very high stresses (known as edge loading)

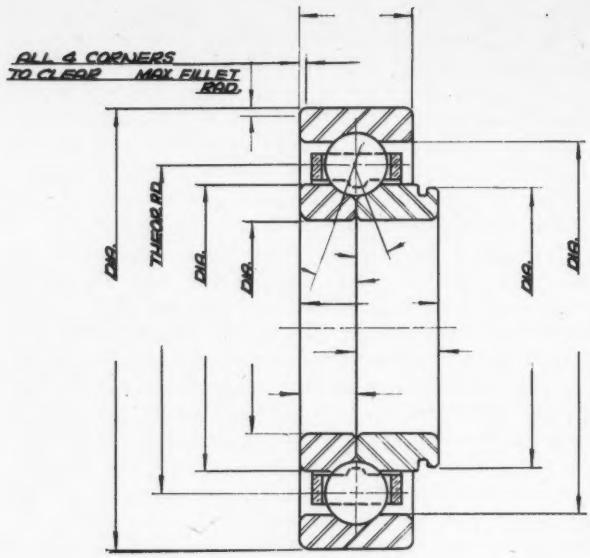


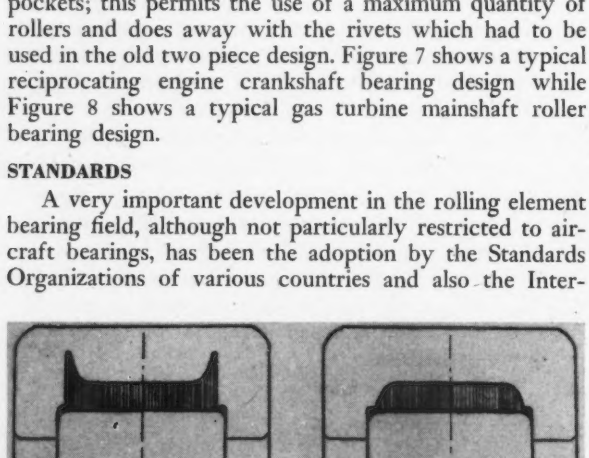
Figure 5
Typical design for split inner ring ball bearing

were present at the ends of truly cylindrical rollers. The introduction of the crown at either end has considerably increased the life of cylindrical roller bearings, which are required to carry particularly heavy loads in prop-jet engines.

A second improvement in cylindrical roller bearings design has been the development of cages with broached pockets; this permits the use of a maximum quantity of rollers and does away with the rivets which had to be used in the old two piece design. Figure 7 shows a typical reciprocating engine crankshaft bearing design while Figure 8 shows a typical gas turbine mainshaft roller bearing design.

STANDARDS

A very important development in the rolling element bearing field, although not particularly restricted to aircraft bearings, has been the adoption by the Standards Organizations of various countries and also the Inter-



Uncrowned rollers or races **Crowned rollers**

Figure 6
Comparison of stresses between crowned and uncrowned rollers

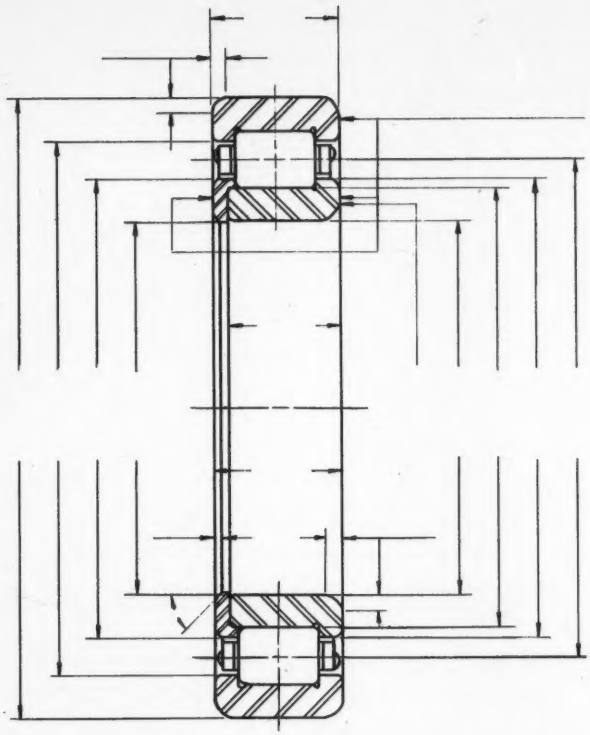


Figure 7
Typical reciprocating engine crankshaft bearing design

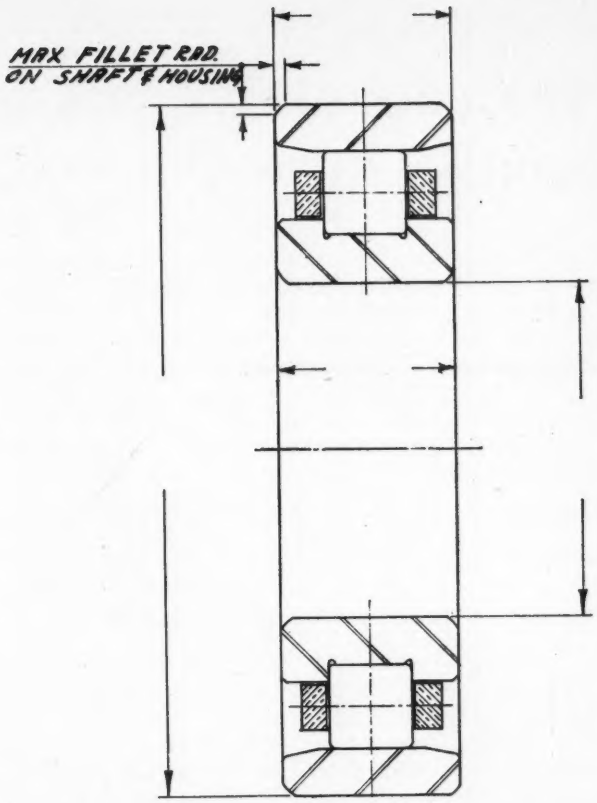


Figure 8
Typical gas turbine mainshaft roller bearing design

national Standards Organization (ISO) of standards in all phases of the bearing industry, with particular reference to dimensional schemes, dimensional and running accuracy tolerances and methods of evaluating loads and load ratings.

The basic dimension plan (Figure 9) provides a properly proportioned scheme for the designer and user to avail himself of and also prevents the bearing manufacturer from having to tool and manufacture an infinite variety of sizes.

The Anti-Friction Bearing Manufacturers' Association has adopted five classes of dimensional and running accuracy tolerances for ball and cylindrical roller bearings, namely Class 1, 3, 5, 7 and 9. Class 1 is applicable to standard catalogue bearings, and most aircraft powerplant bearings manufactured in Canada and the USA are either Class 3 or 5, depending on the application. Classes 7 and 9 are generally restricted to instrument and miniature bearings.

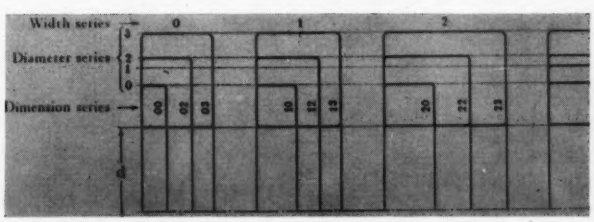


Figure 9
Basic dimension plan for rolling element bearings

THE FUTURE

Along with everyone else, the rolling element bearing industry has to look to the future to see what problems it has to face. Although several come to mind, of particular interest here are those connected with present aeronautical and astronautical research. To the bearing manufacturer this means:

(1) increased reliability,
(2) increased speeds and loads, and
(3) increased temperatures, above 800°F, into a field where liquid lubrication may be impossible.

These subjects, however, must be considered beyond the scope of this paper which, it is hoped, has shown the main developments in the rolling element bearing field with respect to the aviation powerplant field.

ACKNOWLEDGEMENTS

In the discussion concerning the high temperature materials reference has been made to ASLE paper No. 58 LC-16, by T. W. Morrison, H. O. Walp, and R. P. Remorenko of SKF Industries, Inc., Philadelphia.

NON-PROPULSIVE POWER SYSTEMS FOR MISSILES AND SPACE VEHICLES†

by D. K. Breaux* and R. L. Schultz**

AiResearch Manufacturing Company

INTRODUCTION

During the past year or two, much interest has been shown, by those working in non-propulsive power, in the use of power obtained from direct conversion devices. There are several known means of doing this, based on various energy principles and physical effects. The left hand column of Figure 1 presents an abbreviated listing of those direct conversion devices suitable for non-propulsive power. Other means, such as piezoelectric crystals, thermionic emitters, nuclear batteries etc, are recognized but not included. In their present state of development, these have not yet demonstrated sufficient output and efficiency capabilities for most non-propulsive power applications.

In Figure 1, the various energy conversion methods are arbitrarily broken down into two general classifications – namely, primary conversion methods and secondary conversion methods. The primary group consists of devices which convert energy from one of its basic sources to either electricity or heat in one step or process. In contrast, those methods shown in the secondary category accomplish energy transformations, but not directly from one of its prime sources. It might be said that they are at least once removed from energy in its solar, nuclear or chemical state.

As a whole, the primary methods employ devices which may also be classified as static in nature, and the group identified as secondary methods utilize apparatus which may be categorized as dynamic devices. The use of the terms "dynamic" and "static" is intended to imply those devices which in their operation manifest dynamic characteristics as opposed to those which do not.

If the static electric devices are compared with the combination of a combustor and a dynamic device on a specific weight (1 lb/hp) basis, it can be shown that with the present technology, the latter has a definite advantage in most space vehicle applications. In other words, attractive as the primary or static devices are, they are best employed in the space vehicle at relatively low power levels and where long duration operation is required; for example, as the power sources for communications equipment.

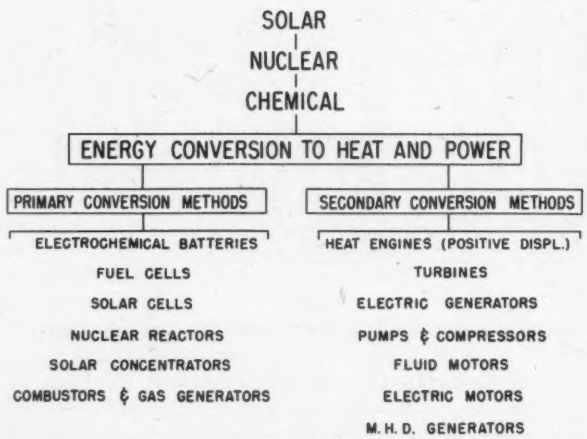


Figure 1
Prime energy sources

From a systems standpoint, the dynamic devices will continue to find applications in the non-propulsive power field simply because, in supplying energy in a variety of forms, can do many jobs conveniently; they mention a few: heating, cooling, mechanical power, fluid power, electrical power etc.

Of course, it may well be argued that the dynamic devices are less attractive from a simplicity and reliability standpoint. It is not felt that this is a point for debate, but rather a point of consideration in choosing a system to best suit a given application.

In fact, it is not intended to weigh the respective advantages or disadvantages of one method or the other. With a close study of a given set of specifications, each will find its best application under conditions and requirements favourable to it. For this reason, it is considered that any attempt to generally optimize has limited results as determined by the initial assumptions which seldom encompass all the details of an actual application. Instead, it is the intent to emphasize the continuing need for dynamic devices, which we must admit still occupy by far a greater percentage of the current engineering effort and business volume.

†Paper read at the Mid-season Meeting of the C.A.I. in Edmonton on the 19th February, 1960.
*Project Engineer, Missile Systems
**Group Supervisor, Preliminary Design

POWER { SHAFT, ELECTRICAL, HYDRAULIC }

COOLING { EQUIPMENT, LAUNCH AND RE-ENTRY, CREW }

HOT GAS { HEATING, ATTITUDE CONTROL JETS, SERVO ACTUATORS }

OTHER MISCELLANEOUS FUNCTIONS

Figure 2

Non-propulsive systems

The capability of the dynamic system, even in its present state of the art, to meet the non-propulsive power demands of future space vehicles is good, and with the prospect of new developments and refinements, such as are to be described to you, its future is strong. It is not felt that the newer direct energy conversion devices will obsolete the dynamic systems. This is considered to be especially true for the case of manned vehicles where environmental requirements are superimposed on power requirements. In such cases the presence of energy in various forms is actually a necessity, nullifying the simplicity advantage of the direct device.

This does not mean that it is intended to discount the static devices. To the contrary, it is planned to nurture their development and growth and, along with the dynamic system, expand their role of the non-propulsive power system in the space vehicle.

PERFORMANCE REQUIREMENTS

It may be generally stated that the non-propulsive power system is to have a major functional role in the space vehicle, equal in importance to the propulsion system itself. Therefore, it would be well to define and size the job it must do. Figure 2 indicates some of the functions provided by the non-propulsive power system and defines its major areas of application in the missile and space vehicle.

The major mission requirements of the non-propulsive power system may be specified in terms of:

(a) mission duration,
(b) power requirements,
(c) cooling requirements, and
(d) duty cycle characteristics.

Let us next look at a comparison of various systems from a standpoint of mission duration and specific weight. In Figure 3 the over-all system weight (per unit of output power) is plotted as a function of mission duration over a wide spectrum of application. The comparison is restricted to those systems which are capable of development in relatively short times, i.e. less than two years. Thus nuclear, solar and isotope systems, while recognized as probable optimum choices for long durations, are not plotted on the graph but are merely indicated by the arrow. It can be seen that for low durations (of the order of ten minutes and less) solid propellant auxiliary power units, battery systems and monofuel systems are competitive with respect to system specific weight. A final choice will be determined by a variety of other factors. For durations of the order of half an hour, monofuel systems appear to be lightest, being considerably lighter than battery systems. For time durations of one hour to in excess of one month, hydrogen-oxygen systems appear to be near optimum and show a substantial weight advantage over the nearest competing system. Typical examples of the power-time duration, extremely well suited to the hydrogen non-propulsive power system, are the one-man one-day and the two-man two-week space vehicle missions. The weight savings shown are actually substantial, as can be appreciated from the logarithmic nature of the plot shown.

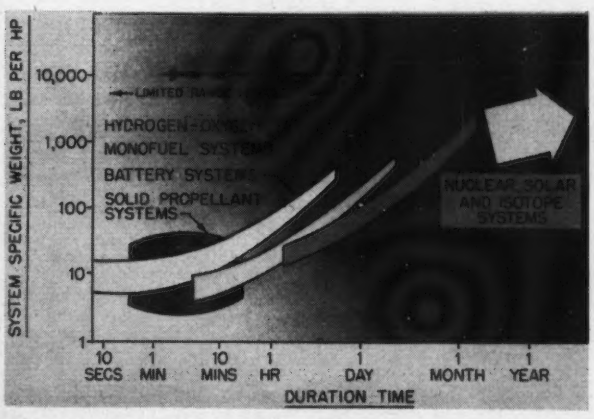


Figure 3

Comparison of non-propulsive systems for power only

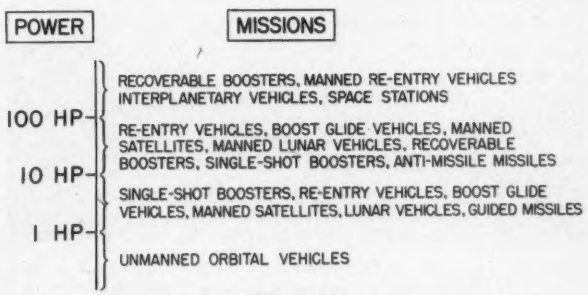

POWER
MISSIONS
100 HP
RECOVERABLE BOOSTERS, MANNED RE-ENTRY VEHICLES
INTERPLANETARY VEHICLES, SPACE STATIONS
10 HP
RE-ENTRY VEHICLES, BOOST GLIDE VEHICLES, MANNED SATELLITES, MANNED LUNAR VEHICLES, RECOVERABLE BOOSTERS, SINGLE-SHOT BOOSTERS, ANTI-MISSILE MISSILES
1 HP
SINGLE-SHOT BOOSTERS, RE-ENTRY VEHICLES, BOOST GLIDE VEHICLES, MANNED SATELLITES, LUNAR VEHICLES, GUIDED MISSILES
UNMANNED ORBITAL VEHICLES

Figure 4

Power requirements for future missions

For purposes of sizing, Figure 4 shows an estimate of the non-propulsive power requirements for the forthcoming generation of space vehicles. In this chart the estimated power requirements for various types of missions are shown, which range from less than 1 hp to in excess of 100 hp. This appears to be the power spectrum for most space vehicles. Less than 1 hp is required only for unmanned orbital vehicles and outputs of more than 100 hp appear to be requirements for some of the advanced projects.

When the cooling requirements for future missions are considered, an extremely wide range is required to

encompass the missions heretofore discussed. As Figure 5 shows, less than 100 Btu per hour are required by infrared detector cryostats and as much as 10 million Btu per hour may be required for re-entry vehicles with human occupants. However, a large bulk of the missions appear to fall in the range of 1,000 to 100,000 Btu per hour.

Turning next to the characteristics of the duty cycles of future missions (Figure 6) two parameters may be examined for indications of future trends. The first parameter is the ratio of average power to maximum power. When the value of this parameter is very low, it indicates large power peaks at some time during the mission. An examination of the previous missions indicates that average power divided by the maximum power falls in the range of 0.1 to 1.0 and attains the latter value only when unmodulated continuous satellites are considered. The second important parameter relates cooling load and power, both of which are measured in units of time-rate of energy flow. This dimensionless parameter is cooling load divided by power. It is zero for small unmanned satellites because there is no need for special cooling. On the other hand, the parameter attains very high values (of the order of 100) for re-entry vehicles,

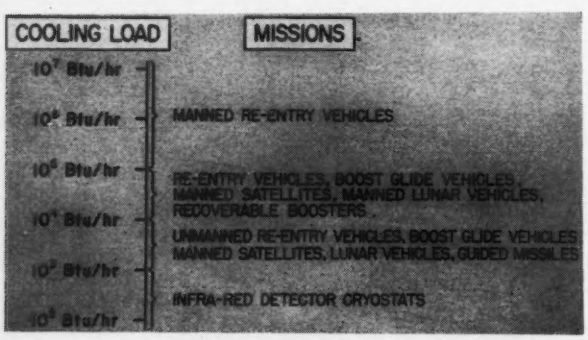


Figure 5
Cooling requirements for future missions

in which case the cooling load dominates the considerations of power. However, most of the missions which have been examined fall into a narrow band of values of cooling divided by power (from 1.1 to 1.5), indicating that heat generated by the production of power is the primary source of the cooling load.

The non-propulsive systems for future missions appear to have a need for very rapid response rates (in the order of 0.10 sec) because of the rapid load changes that occur.

From the examination of future missions we can devise a list of the most desirable characteristics of non-propulsive systems (Figure 7) which are well within the reach of the dynamic type of unit.

Naturally, these systems must have high reliability and low total system weight to minimize costs and attain maximum effectiveness. We have also discovered that future non-propulsive systems must have the capability of producing power and cooling simultaneously. This is a requirement which is not generally recognized, but which will assume greater importance as the high-power-level, high-cooling-load applications make their appearance.

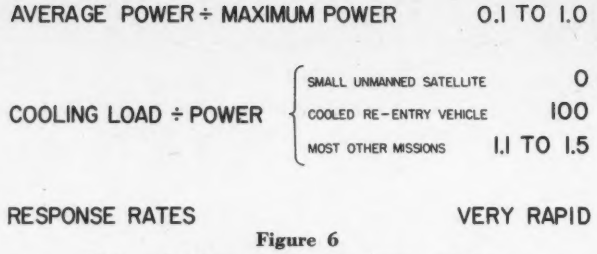


Figure 6
Duty cycle characteristics for future missions

Another characteristic that is desirable in a non-propulsive system is flexibility of power level. It will be extremely advantageous to have system components which can be used for a range of applications involving a wide variation in power and cooling. This would facilitate the advanced development of a non-propulsive system before its final requirements are known. Finally, of course, short development time is a required characteristic in view of the current accelerated space programs.

In endeavouring to advance the state of the art of dynamic systems, we have become convinced that non-propulsive systems based on the utilization of hydrogen have all of these desirable characteristics and, in support of this belief, have hydrogen non-propulsive power systems presently under development which will soon be ready for application.

PROPELLANT SELECTION

The first consideration which suggests the use of hydrogen for non-propulsive power for advanced space vehicles is the premium placed on low specific fuel consumption. This is a necessity for intermediate duration missions. As duration increases for the non-propulsive power system, the fixed equipment weight becomes less and less a penalty as compared with fuel weight. Thus, an improvement in specific fuel consumption and, hence, a potential lowering of weight becomes mandatory for the space application because of limitations in booster payload.

Therefore, it is interesting to consider first what is theoretically possible in the way of minimum specific propellant consumption (spc). By definition:

$$\text{spc} = \frac{2545}{\eta_m \, \eta_{ad} \, H_{ad}}$$

where spc = specific propellant consumption, lb/hp-hr
η_m = mechanical efficiency
η_{ad} = adiabatic efficiency
H_{ad} = adiabatic head, Btu per lb

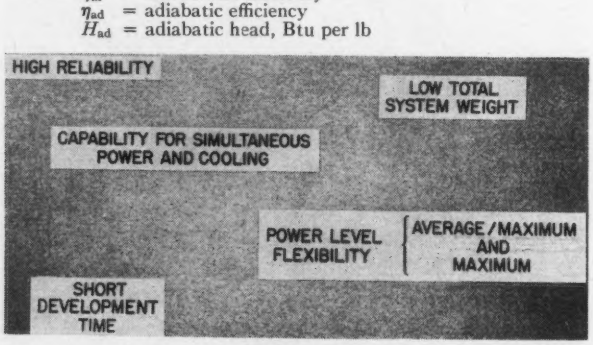


Figure 7
The most desirable characteristics of non-propulsive systems for future missions

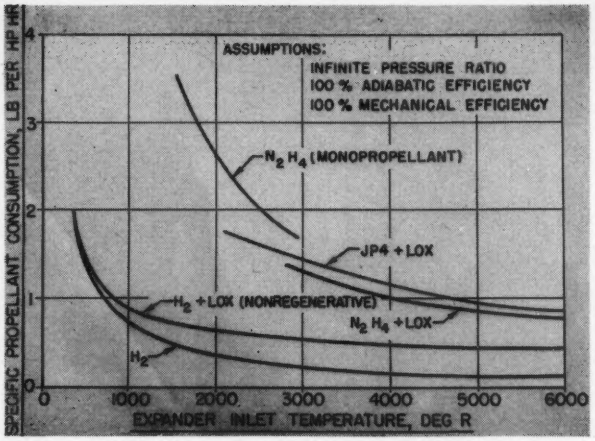


Figure 8
Minimum theoretical specific propellant consumption

Obviously, minimum spc is obtained by maximizing η_m, η_{ad} and H_{ad}.

It can be shown that, for a perfect gas,

$$H_{ad} = \left[\frac{1544}{778}\right]\left[\frac{k}{k-1}\right]\left[\frac{T_{in}}{M_w}\right]\left[1 - \left(\frac{P_{out}}{P_{in}}\right)^{\frac{k-1}{k}}\right]$$

where H_{ad} = adiabatic head, Btu per lb
k = specific heat ratio
T_{in} = expansion inlet temperature, deg R
M_w = molecular weight
$\frac{P_{out}}{P_{in}}$ = ratio of outlet to inlet pressure

For the theoretically perfect case of $\eta_m = 1$,

$$\frac{P_{out}}{P_{in}} = \text{zero:}$$

$$\text{spc} = 1282\left(\frac{M_w}{T_{in}}\right)\left(1 - \frac{1}{k}\right) \text{ lb/hp-hr}$$

Thus, high temperature, low molecular weight and low specific heat ratio all tend to decrease spc.

Figure 8 shows a comparison of several propellants under the assumptions of infinite pressure ratio and 100% adiabatic and mechanical efficiencies. The values shown represent what is theoretically possible for these propellants in terms of specific propellant consumption versus the gas temperature at the inlet of the expander. It should be noted that the assumptions made above are extreme ones. They afford a useful basis of comparison but, involving an exit temperature of 0°R, are not to be taken as the limit of realizable performance, even with vacuum exhaust.

The monopropellant hydrazine and three bipropellants (JP-4/LOX, Hydrazine/LOX, and Hydrogen/LOX) are shown. The lowest curve marked H_2 represents the ultimate case where the working fluid is pure hydrogen, heated to the temperatures indicated without combustion. This could be done either by means of various nonchemical heat sources such as nuclear or solar heaters or as a result of using the hydrogen as a coolant in the vehicle. The latter means of heating hydrogen is extremely promising for certain applications where high temperature heat sources are available, such as re-entry vehicles.

Inspection of Figure 8 reveals that it is theoretically possible to achieve an spc of less than 2 lb/hp-hr with the more conventional propellants such as hydrazine, provided sufficiently high values of efficiencies, pressure ratios and temperature are used. However, the practical limitations of materials and efficiencies actually attainable indicate that an spc of 3 lb/hp-hr is probably the lower limit for the conventional fuels.

On the other hand, spc's considerably less than 2 can be achieved with the hydrogen-oxygen combination without resorting to extremely high temperatures. Since the incentive for low propellant weight is so great in long duration applications, it is concluded that present programs should definitely be oriented toward the use of hydrogen as a fuel.

From basic chemistry, as shown above, it is obvious that pure hydrogen is the optimum working fluid from a molecular weight standpoint. In addition, hydrogen offers the advantage of having a high heat of combustion relative to other fuels. Table 1 shows the approximate heating values of some of the typical fuels.

TABLE 1

Fuel	Heat of combustion Btu per lb of fuel
JP-4 + Oxygen	20,000
Hydrazine (decomp)	1,233
Hydrazine (95%) + Oxygen	6,810
Hydrogen Peroxide (99%)	678
Typical solid propellant	1,000
Hydrogen + Oxygen	51,500

The high heating value requires that a minimum amount of the hydrogen be combusted to achieve a given inlet temperature. Since, for a practical system, there is a defined limitation on prime mover inlet temperature because of material limitations, a hydrogen-fueled secondary system requires the use of only a small amount of oxygen to meet the design inlet temperature, thereby keeping the molecular weight low. Typical molecular weight of a hydrogen-oxygen working fluid for a secondary system is approximately 3.5 as compared with 2 for pure hydrogen and 18 for stoichiometric combustion to water.

A further advantage of hydrogen is its large cooling capacity, a highly desirable feature in space applications where heat rejection is a major problem. The possibility of absorbing the heat equivalent of all of the power system output power by the hydrogen fuel is discussed in the next section.

CYCLE ANALYSIS

A fundamental concept in the design of an open-cycle power system for a spacecraft is that the vehicle operates in a zero ambient pressure environment for a major portion of its design mission. This operating condition, when applied to the power system through a reasonably sized exhaust, means exceedingly high pressure ratios are available at modest values of absolute inlet

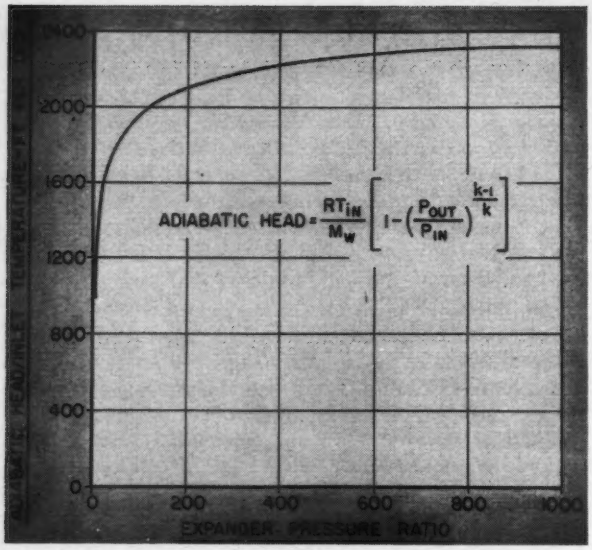
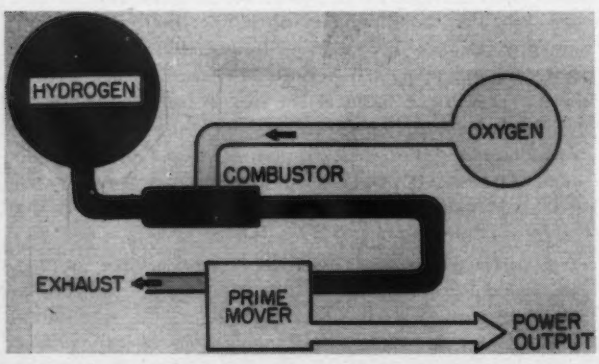


Figure 9
Adiabatic head of hydrogen

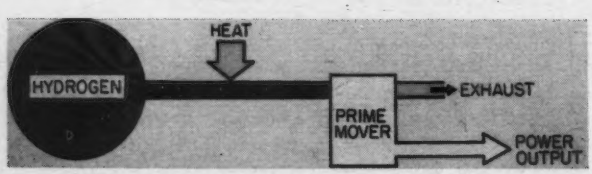
pressure. Thus, the availability of a pressure ratio of the order of several hundred to one thousand, at inlet pressures of 200 to 300 psia or less, is a major factor in selecting the prime mover type for the space power system.

As may be seen in Figure 9, the adiabatic head increase per unit of pressure ratio increase above ratios of 200 to 1 diminishes rapidly. Thus, a prime mover may be designed to use this high pressure ratio and yet a high absolute inlet pressure is avoided, along with its ensuing system weight penalty.

If we then use a design pressure ratio greater than 200, the specific fuel consumption at a prescribed prime mover inlet temperature becomes primarily a function



Simple hydrogen system for power only



Pure hydrogen system for power and cooling

Figure 10

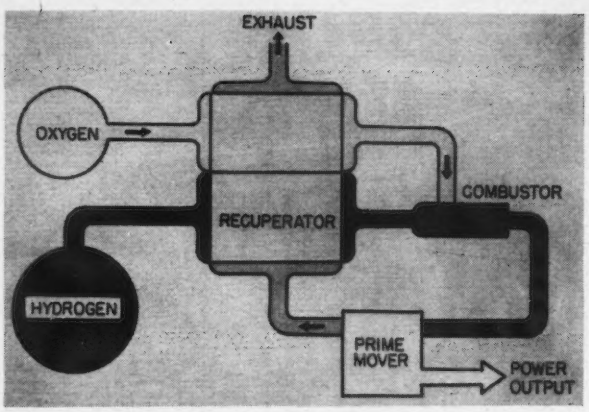


Figure 11
Recuperative hydrogen system for power only

of the prime mover efficiency and the molecular weight of the working fluid.

Several basic hydrogen cycles have been analyzed. Four of these are shown schematically in Figures 10, 11 and 12. The simplest cycle is shown in Figure 10. In this system, there is a combustor in which oxygen is added to the hydrogen. The resulting hot gas is delivered to the prime mover which contains an expansion engine. The prime mover converts the heat energy in the hot gas to useful power output as indicated. The exhaust from the prime mover is discharged overboard in this system. Note that the oxygen is carried only in order that the temperature of the hydrogen can be increased. Much less than the stoichiometric proportion of oxygen is required. Instead of 8 lb of oxygen, about 0.1 to 0.6 lb of oxygen per lb of hydrogen is used.

The pure hydrogen system is also shown in Figure 10. As shown in this system the oxygen has been eliminated completely, thus affording the opportunity for minimum propellant weight. Of course, heat must be provided and is shown diagrammatically as attained from any external source. This cycle, one of the simplest concepts, has particular validity for re-entry vehicles since the aerodynamic heating experienced during the re-entry phase far overshadows power-generated heating. Thus, the system can be used for both power and cooling under these

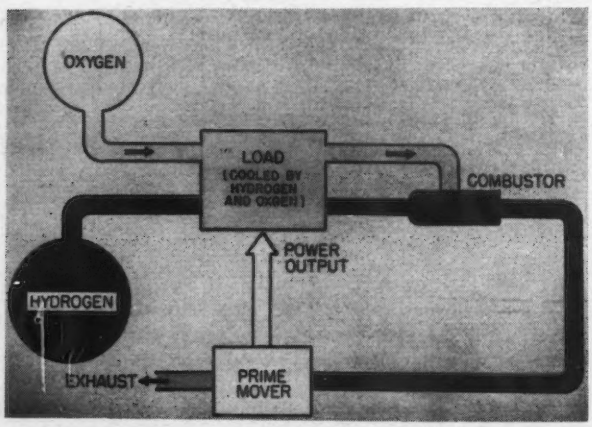


Figure 12
Feed-back hydrogen system for power and cooling

circumstances with the cooling load predominating. It should also be stated that the diagram shown is equally valid for other sources of heat, such as nuclear, isotope or solar sources.

There are many ways to improve performance of the previously shown simple cycle for power only. Figure 11 shows one example of such an improvement. In this case, the energy in the hot exhaust gases from the prime mover is utilized to preheat the hydrogen and oxygen in a recuperator. This recuperative system provides a reduction in the amount of oxygen, since less is required to attain the prime mover inlet temperature.

Another way of improving the spc of the simple system is the output feed-back cycle shown in Figure 12. In this case, the amount of oxygen required is again reduced by preheating the hydrogen but, in this case, the preheating energy is obtained from the power output of the prime mover rather than the exhaust gases. The useful power output of the prime mover is delivered to the load and there appears eventually as heat. If this load is cooled by the hydrogen and oxygen, a twofold purpose is accomplished. Thus, this system accomplishes two major functions, namely, power and cooling. This illustrates the versatility of hydrogen as a fuel in secondary systems.

The comparison of the above-mentioned cycles on the basis of specific propellant consumption for particular values of expander inlet temperature and expander pressure ratio is shown in Figure 13. The simple hydrogen-oxygen cycle obviously requires the highest propellant weight for a given expander efficiency. The pure hydrogen cycle, which uses no oxygen but requires external heat, has the lowest spc. The curves for the output feed-back and recuperative cycles lie between the other two. It is important to know that specific propellant consumption below 1 lb/hp-hr is attainable with a reasonably efficient expander, provided that the proper cycle is selected.

PRIME MOVER SELECTION

The selection of the appropriate prime mover for a given non-propulsive power system is a complex matter. The inter-relations between such vital areas as performance, size, weight, complexity, reliability, cost, suitability to envelope limitations and delivery time can rarely be formulated so that it is perfectly clear which course to take. Occasionally, however, certain factors so outweigh the others that the choice is nearly self-evident; such is the case with hydrogen-fueled power systems.

Two principal characteristics of hydrogen as noted previously were, first, its extremely high energy per unit mass, or adiabatic head and, second, its low density. With an adiabatic head of the order of 2.4×10^6 ft lb/lb, the prime mover is forced to be a multistage device in order to make efficient use of this available energy. Energy extraction capabilities of a single-stage device are limited by stress levels, size and speed or other mechanical problems.

The low density of this system propellant (less than 0.2 lb/cu ft at the prime mover inlet) leads to fairly high volume flow rates through the prime mover; in addition, for space vehicle operating conditions, the exit volume flows become quite sizeable. As a result, the type of machinery to be used must be capable of handling rather large volume flows and at the same time must be adaptable to multistaging.

Two main contenders arise from a survey of possible prime movers for the low to medium horsepower application; namely, the multistage turbine and the piston-type positive displacement engine. A decision as to which of these designs should be preferred can not be made without an extensive thermodynamic analysis and design study of both these types.

PISTON EXPANDERS

In the study of piston-type expanders, it is necessary to consider not only the possible piston engine cycles but also the other main influencing factors such as the heat transfer in the cylinders and the mechanical and friction losses inherent in piston-type designs. The latter items increase in importance when power levels as low as 1 hp are to be considered. The interesting result of a study of this type shows that the efficiencies obtainable with piston-type expanders at the high gas temperatures and pressure ratios required for reasonable spc's are considerably lower than those quoted for hydraulic motors. In particular, with normal development effort, efficiencies of only 35% to 45% are obtainable with a single-stage machine. The analysis also indicates that it is quite difficult to obtain higher efficiencies since heat and mechanical losses limit to a considerable extent the piston engine performance.

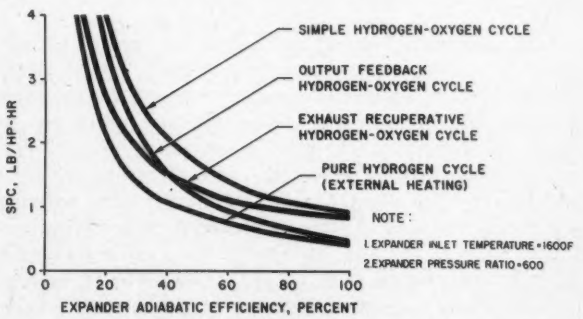


Figure 13
Specific propellant consumption of several hydrogen systems

An attempt to increase efficiency by multistaging reveals that the low mean effective cylinder pressures for consecutive stages will soon approach the level of the mean friction pressure, thus resulting in negligible power increase. In order to avoid this, the entire cycle has to be lifted into the higher pressure regime. This points out one of the main differences between piston expanders and turbines; namely, that the turbine can accommodate itself successfully to an inlet pressure range as low as 1.0 to 0.010 psi while the piston expander favours inlet pressures as high as 500 psi, which pressure would require the use of fuel boost pumps, with attendant increase in complexity and decrease in reliability.

TURBINE EXPANDERS

A study of turbines, including both the standard, multistage, partial-admission turbines and the re-entry type of turbine, and covering a range of stage numbers,

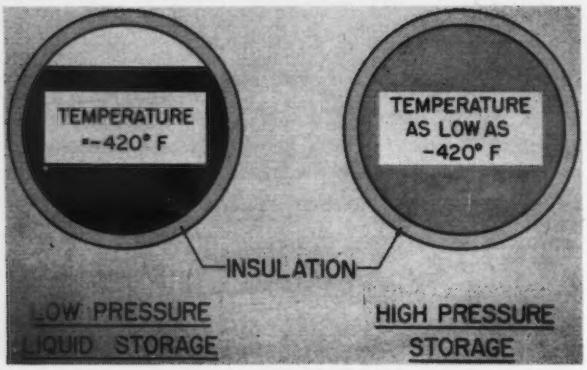


Figure 14
Methods of storing hydrogen

sizes and speeds, shows that efficiencies can be made very high if enough stages are used. This is not a surprising result, since the benefits of multistaging are well known; but, efficiencies of greater than 70% are potentially of great interest in orbital vehicle secondary power applications, and such magnitudes are attainable in turbines without serious increase in design complexity. That is, adding stages in a turbine is a fairly straightforward procedure, whereas multistaging in positive displacement machinery generally involves direct increases in complexity and weight and offers diminishing rewards in efficiency.

An additional important factor in favour of the turbine, is the large growth potential. Power level changes can be achieved by merely controlling the inlet pressure and, because the design pressure ratios are so high, no noticeable changes in efficiency occur. The inlet pressure may be increased – and, therefore, the flow and power – by about 10 times the design value without significant changes in the system. Fuel tank strength is the limiting factor and, of course, this can be increased with an increase in tank weight if the over-all system considerations warrant it. Similarly, reductions in power are accomplished by throttling to reduce the mass flow, with an additional effect due to a reduction in adiabatic head with diminishing pressure ratio.

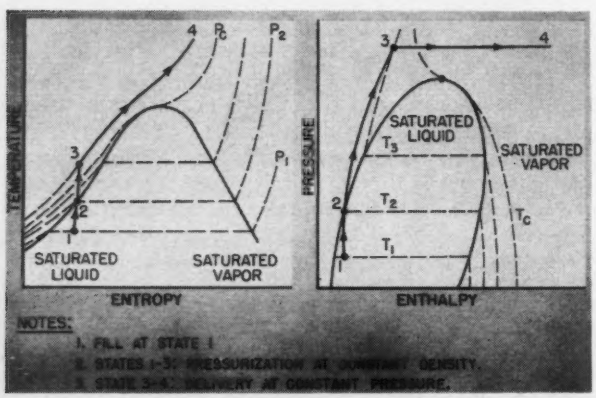


Figure 15
Supercritical storage system operation

PROPELLANT TANKS

As is generally realized, tankage size and weight are of major importance in the design of a hydrogen-oxygen-fueled power generating system. Both of these fluids are best stored at cryogenic temperatures in order to obtain maximum fuel density. Minimization of tankage weight thus involves careful thermal design to avoid propellant loss by vaporization or venting. The hydrogen tank requires the most consideration in this respect because of its relatively large volume.

The space vehicle environment is particularly favourable for cryogenic storage in one major respect. The tank ambient is a practically pure vacuum; the only heat transfer to the fuel (aside from conduction through a structural support) is by radiation from compartment walls and external equipment. This eases the insulation problem considerably.

The zero gravity condition associated with space flight affects the fuel tank design in two respects. First, if the fuels are stored as liquids, positive design techniques must be employed to insure single phase withdrawal. Second, it necessitates pressurized fuel transfer. One advantage of the turbine prime mover system is that the latter requirement is not critical because of the moderate fuel pressures required for operation.

Tankage design studies and tests indicated that two general methods of fuel storage can be considered most suitable. These are (a) low-pressure storage of either or both fluids as liquids, and gas phase fuel withdrawal as shown in Figure 14 – here the tank design involves a flexible bladder to separate the liquid from the gas and matching evaporation rate to fuel use rate – and (b) storage at supercritical pressures and low temperatures where the tank fluid can be maintained as a single-phase fluid throughout operation as also shown in Figure 14. Studies of a variety of storage techniques indicate that both storage methods lead generally to similar tankage weight and space requirements, but that minimum system complexity results from storage at the supercritical conditions.

The supercritical storage method can best be illustrated by referring to Figure 15, which shows pertinent thermodynamic states on schematic pressure-enthalpy and temperature-entropy diagrams. The tank is charged with low pressure liquid (Point 1) and is capped off; heating of the fluid prior to use results in pressurization at constant density. Liquid and vapour can co-exist in the storage space until saturation conditions (Point 2) are reached; with further heat input, the fluid stored becomes homogeneous, with properties similar to those of a compressed liquid.

Prior to withdrawal, the tank fluid is heated until pressure becomes supercritical (Point 3); here the temperature is below critical (59.8°R for hydrogen). During withdrawal, heat is supposed to maintain supercritical pressures; as indicated on Figure 15, fluid temperature rises during operation. It is to be noted, however, that single-phase storage is possible using this method. When the tank is nearly empty, pressure may be allowed to fall without encountering liquid dropout; heat input requirements may, thus, be relaxed during the last phase of operation.

This storage method eliminates phase separation problems completely and is ideally suited for zero-gravity problems. Of major importance, a system using this technique is insensitive to gravity environment and may be evaluated by ground testing, thus simplifying system development.

The specific design of the tank system components, i.e. insulation materials etc, depends upon the desired mission, operating pressure level, withdrawal rate range, flight environment and ground hold requirements. Tankage system and pressure level affects fuel container shell weight directly and also determines the energy required for pressurization during fluid delivery, since operating pressure also influences the thermodynamic characteristics of a supercritical storage system. The degree and type of insulation for the tank is determined by the surroundings, the tank and by the heat input power and delivery rate requirements for a given mission. With respect to propellant delivery rate, insulation is provided to match container heat leak with tank input energy required.

CONCLUSION

It appears that the non-propulsive power system of the future will be composed of a variety of power sources and energy converters. A static conversion device probably will be employed for a long-time low-power lever application, i.e., communication and illumination. A dynamic converter will be employed, possibly with intermittent operation, to supply compartment air conditioning, and another dynamic converter to supply vector-steering and additional cooling for re-entry. It is obvious that the static or primary conversion devices are going to supplement and not replace the secondary or dynamic conversion devices.

In the non-propulsive power systems required to operate for durations of from one hour to one month, the hydrogen powered system appears to be extremely attractive. Figure 16 graphically illustrates some of the outstanding characteristics of hydrogen and indicates, on the right, what effects these have on non-propulsive systems. Hydrogen is represented by the shaded bars, and the comparative substance is indicated by the labelled unshaded bars. Of major importance are the high heat of combustion of hydrogen (from two to three times that of normal JP fuels on a weight basis) and the high specific heat (some fourteen times that of air). If hydrogen is used in non-propulsive systems, the effects of these two characteristics usually are: (1) a substantial reduction of the total weight of fuel which must be carried (as indicated by the upper right-hand comparison), and (2) a corresponding reduction of the over-all system weight. The principal disadvantages of hydrogen are related to its high volume. The specific volume of hydrogen gas is much higher than that of a gas such as air, as indicated in the chart, and the specific volume of liquid hydrogen is also much higher than that of the typical liquid, water. However, because of the high energy content and the specific heat of hydrogen, the total volume of fuel which must be carried is not as excessive as might first be expected. The right-hand side of the chart indicates that only from two to three times the volume of the comparable monofuel is required.

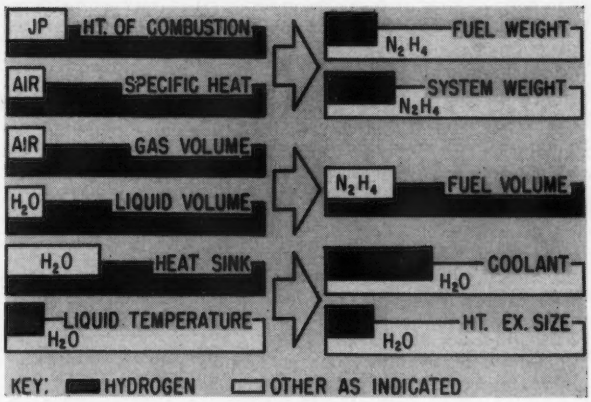


Figure 16
Hydrogen characteristics and their effects on non-propulsive power systems

Two additional outstanding advantages of hydrogen are derived from its heat sink characteristics. When heating to room temperature is considered, liquid hydrogen will absorb about twice as much heat as the same weight of water, the usual high-capacity coolant. Also, liquid hydrogen coolant is stored at the extremely low temperature of 40°R (shown on the chart on an absolute scale). It is far less than the storage temperature of water. The effects of high heat sink capacity and low initial temperature of liquid hydrogen are: (1) only about half as much hydrogen need be carried to accomplish a given cooling job, and (2) because of the large temperature differences that exist in hydrogen heat exchangers, size and weight are very much less than with exchangers using water as the coolant.

COMMENTS ON THE EVOLUTION OF AIRCRAFT MAINTENANCE†

by I. J. Kessler*

United States Air Force

INTRODUCTION

Operations analysis in USAF

We in operations analysis are interested in aircraft maintenance because of its magnitude and particularly because of the critical restrictions it places on flying.

The impact of maintenance on military resources is tremendous. 33% of our personnel and 40% of our operating budget are required for maintenance, to say nothing of the huge logistics system that is required to distribute these resources to the points where maintenance can use them.

Since our aircraft are designed for maintenance, the rate of flying that we can do is automatically limited by the rate of maintenance that we can provide.

Because of the importance of maintenance to the accomplishment of our mission, we have put forth much effort to define its characteristics and to determine effective ways to measure, distribute and control our maintenance resources.

My remarks are based on eight years of research with airlines and military agencies, and I must tell you at this time that the remarks I am about to make are my own and do not necessarily represent USAF policy.

STATE OF THE ART AND PHILOSOPHY

I will touch briefly on the trends in manpower productivity that have developed over the last decade, as a measure of the advance of the maintenance art, and discuss what I believe to be its underlying philosophy as a background for the discussion of maintenance concepts which will follow.

Domestic airline industry

Figure 1 shows the increase in productivity that was achieved by the domestic airline industry as a whole between 1947 and 1955.

The data were taken from CAA records and reduced to the proportion of a single average airplane.

(a) Utilization remained constant at 6.5 hours per day.

(b) The average of 20 mechanics per airplane remained constant over the period.

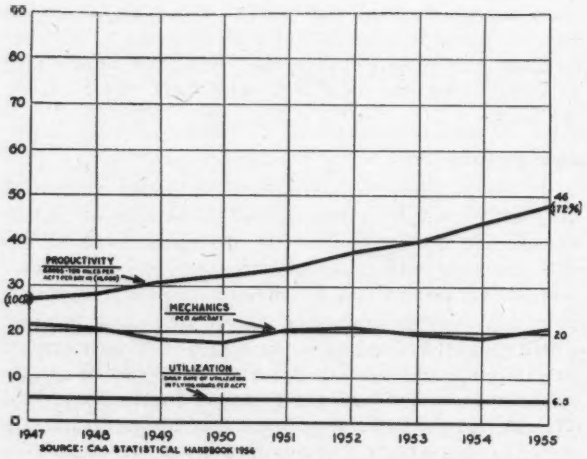


Figure 1
Gross-ton-mile productivity per mechanic as utilization remained constant

(c) The productivity of maintenance increased 72% due to the introduction of larger faster aircraft. This increase is expressed in a common denominator – gross-ton-miles.

United Airlines fleets

Figure 2 shows similar increases in manpower productivity by specific fleets operated by United Airlines.

However, on this chart the increases in productivity are expressed in terms of reductions in direct labour man hours required per flying hour.

(a) DC 6 m/h per f/h were reduced from 28 to 7 in 10 years.

(b) CV 340 m/h per f/h were reduced from 14 to 5½ in 5 years.

(c) DC 7 m/h per f/h were reduced from 15 to 9 in 4 years.

It is obvious from these exhibits that the art of maintenance has advanced dramatically. It has, in my opinion, moved ahead of the technological advance of the aircraft industry.

Maintenance philosophy enhances progress

The basic philosophy of aircraft maintenance, whether it be civil or military, may be summed up as, "the support of a safe, dependable operation at a reasonable cost".

†Paper read at the Mid-season Meeting of the C.A.I. in Edmonton on the 20th February, 1960.
*Operations Analyst

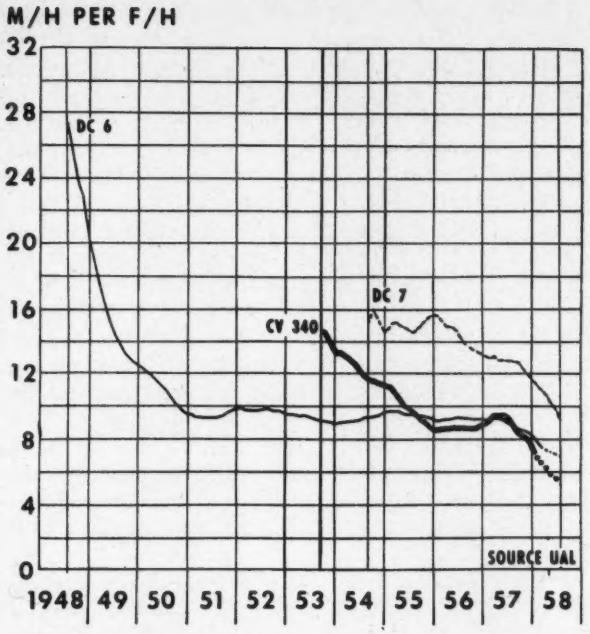


Figure 2
Man hours per flying hour
(12 month moving averages)

This philosophy is preventive in nature; it is based on caution which stems from:

(a) fear of mechanical failure,

(b) ignorance of the performance of new components and the safety aspects of such failures as may occur, and

(c) the pressure of regulatory bodies.

This concession to caution demands extensive overmaintenance in the early years of fleet operation.

The desire for a reasonable cost, on the other hand, demands constant effort to reduce overmaintenance provided this can be done without sacrificing safety or reliability.

This conflict between caution and reliability continues to dominate the process of performance improvement throughout the life of the fleet. It protects and enhances reliability as new techniques are introduced to increase maintenance productivity.

With this background in mind we can proceed to the discussion of concepts of maintenance.

Repair and replace concept

The repair and replace concept is the traditional one in the industry; it dates back to the beginning of our aircraft operation.

Because repair and replace requires the rotation of components, the term "rotables" is used quite generally to describe the category of components which can be repaired and replaced and to distinguish them from the category of items which have only a one-time use and which, therefore, become disposable at failure.

Possibly the most interesting way to present the repair and replace concept is to follow its evolution. In addition, this technique will lead quite naturally into the examination of disposal at failure which is to follow this discussion.

Early design

The tendency of early designers to combine subsystems into complex major components provided the basis for both repair and replace and rotation.

The repair of these complex components in place was time-consuming and often delayed the airplane.

In order to avoid aircraft delays, failed components were removed and replaced by good ones.

Because these complex components were expensive, they were, of course, repaired and returned to serviceable stores. This process became known as the rotation of repairable components.

Provisioning

In order to support rotation, it was necessary to provision spares more or less as indicated in Figure 3.

Provisioning simply meant that adequate numbers of components had to be procured to satisfy the requirements of all phases of operations and maintenance, and also to provide sufficient additional units to satisfy the requirements of rotation without causing delays due to shortages in any of these phases.

CAA time control

With the advent of the Civil Aeronautics Act of 1938, CAA began to regulate the times between inspections and overhauls for major aircraft components.

(a) Original time limits were established by mutual agreement between CAA, the manufacturer and the airlines.

(b) Provision was also made for the extension of these time limits as and when such extensions were justified, either by additional experience with a component or by improvements in its reliability.

Overhaul

To facilitate compliance with this time control regulation, it became desirable to return the service time of components to zero as they were reworked to return them to a serviceable condition.

The rework required to return time to zero was often much more extensive than the repair required to

PROVISIONING OF R 2800 ENGINES		SUPPLY / MAINTENANCE
Installed on aircraft	262	72.6%
Serviceable station spares	6	1.7%
Serviceable base spares	14	3.9%
SUB-TOTAL SERVICEABLE ENGINES	282	78.2%
In transit from field stations	4	1.1%
Awaiting mount tear-down	5	1.4%
In mount tear-down	3	.8%
Bare engines awaiting engine-tear-down	12	3.3%
In overhaul—tear-down to test cell	42	11.6%
Awaiting nacelle build-up	9	2.5%
On nacelle build-up line	4	1.1%
SUB-TOTAL IN MAINTENANCE	79	21.8%
TOTAL ENGINES	361	100%

Figure 3
Provisioning for the rotation of repairable components

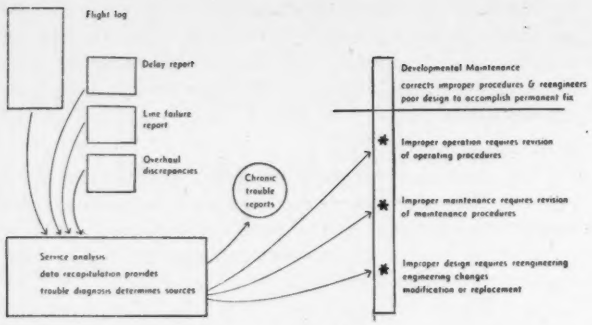

Flight log
Delay report
Line failure report
Overhaul discrepancies
Chronic trouble reports
Service analysis
data recapitulation provides
trouble diagnosis determines sources
Developmental Maintenance
corrects improper procedures & reengineers poor design to accomplish permanent fix
Improper operation requires revision of operating procedures
Improper maintenance requires revision of maintenance procedures
Improper design requires reengineering engineering changes modification or replacement

Figure 4
Aircraft performance analysis

return the component to a serviceable condition. Hence the term "overhaul" is used to describe the more extensive process which allows returning component time to zero.

Performance analysis

Management soon realized that the provision for extensions of time between inspections and/or overhauls presented a golden opportunity for the reduction of maintenance costs provided, of course, reliability could be retained or improved.

The various methods employed to exploit this potential economy finally culminated in the technique called "performance analysis" which is illustrated by Figure 4.

Here we see daily working documents being scrutinized constantly to determine causes of failure which fall into three categories:

(a) those due to improper operation,
(b) those due to improper maintenance, and
(c) those due to improper design.

As incidents of failure develop into trends, chronic trouble reports warn maintenance of the location and magnitude of these budding trouble areas.

Developmental maintenance

With these quantitative patterns of failure as a guide, maintenance took extensive action, not only to repair but to permanently correct causes of recurring failures. This technique, called "developmental maintenance", pursues the permanent fix by:

(a) revising improper operating procedures,
(b) revising improper maintenance procedures, and
(c) re-engineering improper designs.

Overhaul patterns indicate progress

The progress achieved under repair and replace maintenance is presented graphically by the overhaul patterns of the three fleets studied at United (Figure 5).

The history of earlier fleets is not included because it was only with the introduction of the DC 6 fleets that maintenance took on a certain amount of sophistication in its management policies.

Even so, DC 6 development was slow; airframe overhaul began at 700 hours in 1947 and progressed gradually in 100 hour increments to 2000 hours in 1954. It had advanced to 3000 hours in 1959.

R2800 engine development in the DC 6 followed a similar slow laborious pattern; it dropped behind the airframe pattern at 1600 hours but reached 2300 hours by 1959.

Introduction of the CV 340, however, shows an advance in maintenance thinking. The accumulation of experience with the DC 6 appeared to justify starting CV 340 airframe overhaul at 1000 hours in 1952, and good performance justified advancing it rapidly to 2000 hours in 1954, and on to 2500 hours by 1959.

The R2800 engine in the CV 340 remained constant at 1100 hours for five years because of a conservative attitude toward two-engine aircraft and some difficult problems. It had, however, advanced to 1800 hours by 1959.

Introduction of the DC 7 shows another even greater advance in maintenance thinking; airframe overhaul began at 2000 hours in 1954 and had advanced to 3500 hours by 1959.

The R3350 engine, being a new component, was started at 800 hours and, because of its poor performance, advanced slowly. It had, however, reached 1400 hours by 1959.

This process of advancement in maintenance thinking has carried over to the DC 8 program. Airframe overhaul is starting at 2500 hours in spite of the DC 8's entirely new and drastically different design philosophy.

The history of the repair and replace concept can be summed up as one of continuous progress characterized by constant increases in manpower productivity that were achieved concurrently with constant improvement in aircraft reliability.

DISPOSAL AT FAILURE

Evolution in hardware

As the repair and replace concept developed, the feedback from maintenance, along with continued research by the manufacturer, brought about a considerable change in the hardware of the aircraft industry:

(a) complex components gave way to simpler ones,
(b) sub-assemblies became replaceable,
(c) modular systems appeared,

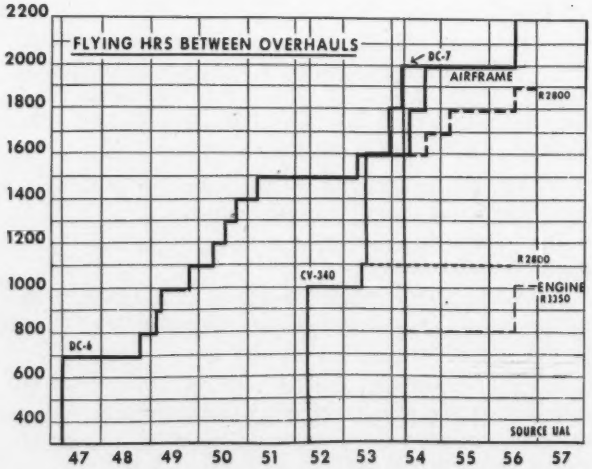


Figure 5
Overhaul patterns: airframe and engine

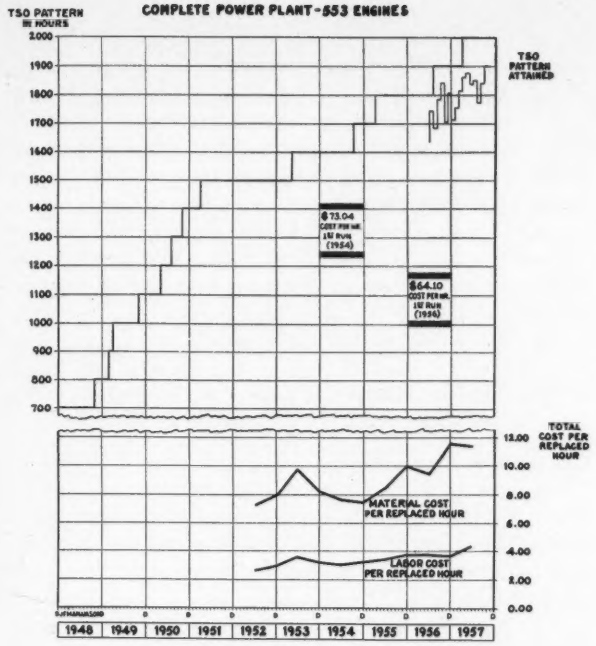


Figure 6
UAL — history of the development of the R2800 engine

(d) accessibility was provided for critical components, and

(e) replacement of components became relatively quick and easy.

New design concept

Possibly the most interesting of these hardware improvements is the new concept of design for disposal at failure.

This new concept presents some very plausible assumptions:

(a) Cost of manufacturing components could be appreciably reduced by using non-repairable designs and automated production techniques such as printed circuitry, dip soldering etc.

(b) Reliability could be considerably increased by potting, sealing, canning etc, which would also preclude repairs.

Approaches to evaluation

In view of the potential economy and reliability presented by this new concept, it becomes desirable to develop a technique for its evaluation or at least some method for comparison by which a logical choice can be made between these two concepts.

(a) If we set out to evaluate disposal at failure, we are immediately faced with the many unknowns that go along with new design, particularly in the electronics field where this new concept offers its greatest promise.

(b) If, on the other hand, we decide to re-examine the repair and replace concept, we can use the type of data that I have used here, which is abundant and accurate both as to performance and cost.

R 2800 engine development

The history of development of the R2800 engine, Figure 6, shows how this already available data can be used to re-examine the effectiveness of the overhaul process:

(a) It shows that reliability has been retained and greatly improved.

(i) The stepped line running diagonally across the chart shows repeated increases in time between overhaul.

(ii) The irregular lines in the upper right-hand corner marked "TSO Attained" show that in actual practice, engines are attaining over 95% of the time allowed between overhaul.

(b) It shows that overhaul is economical because:

(i) the cost of an engine hour replaced by the overhaul process was only $11.50 in 1957 after most of the engines in the inventory had been overhauled many times, and

(ii) the first-run cost of an engine hour would have been $73.04 in 1954 and $64.10 in 1956.

Admittedly these engines were not designed for disposal at failure which would probably have made some difference. However, to date I know of no engines that have been successfully designed for disposal at failure.

The point of real importance here is the reliability-economy relationship that we find as the result of an increasing trend in reliability. This is partly obscured by the inflationary rise in the cost per engine hour replaced, which is shown by the upper or total line in the lower half of the chart.

Experience under the repair and replace concept shows that mechanical devices generally follow this pattern of increasing reliability. Since data are available for most mechanical components, an evaluation of overhaul effectiveness such as this should not be difficult.

Electronics nonconformity

The history of electronics equipments, however, has differed from the history of mechanical equipment in many ways:

(a) The random and sometimes erratic patterns of failure have been much more difficult to evaluate.

(b) The repair and replace approach did not produce clear-cut increases in reliability in electronics equipment as it did in mechanical devices.

(c) True electronic performance data has not been easy to collect in the past because of the lack of "on time" timers, "on and off" stress counters etc.

As a matter of fact, the tendency of the industry has been to avoid involved inspection and overhaul procedures and to go to an "on condition basis" for electronics maintenance.

These difficult conditions, plus the fact that data on electronics are not so readily available as they are on mechanical devices, suggest that the approach to the evaluation of overhaul effectiveness for electronics equipment should, at this time at least, be on a theoretical rather than a practical basis.

Theoretical approach

The theoretical approach is based on the same principles that were used in the evaluation of the R2800 engine. Retention of reliability is considered to be of first priority and economy of secondary importance.

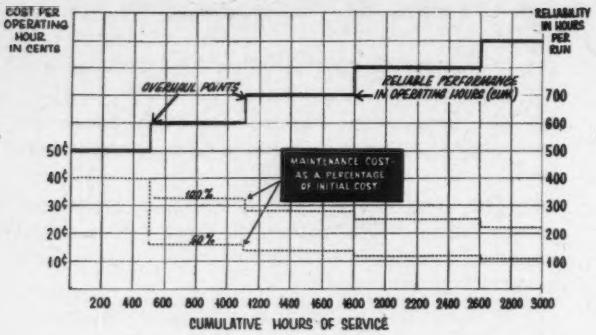


Figure 7

Increasing reliability with repeated overhauls of an economically repairable component

In this approach we consider two likely trends, increasing reliability and decreasing reliability. Both are projected at extreme rather than normal rates in order that we may observe the factors upon which the decision must rest in one brief exercise for each trend.

The case of increasing reliability

Figure 7 shows increasing reliability similar to the engine example used earlier except that its increase in reliability is constant and at an accelerated rate of 100 hours for each overhaul.

The cost per overhaul also remains constant. Two costs are shown: in the first the cost per overhaul is equal to the cost of a new component or 100%; in the second, overhaul cost is 50%.

Assuming the new component cost to be $200.00, and ignoring possible salvage value, the cost per hour for the first run of 500 hours is 40c an hour. Since cost per overhaul remains constant and hours of service per overhaul increase with each overhaul, it becomes obvious that the cost per hour of use must be reduced with each overhaul.

Although hypothetical and totally unrealistic, this chart does convey the impression of what might generally be expected if the overhaul process is capable of increasing reliability.

The case of decreasing reliability

Figure 8 shows decreasing reliability. All values remain the same except for the fact that the overhaul process loses reliability at the rate of 100 hours of service per overhaul.

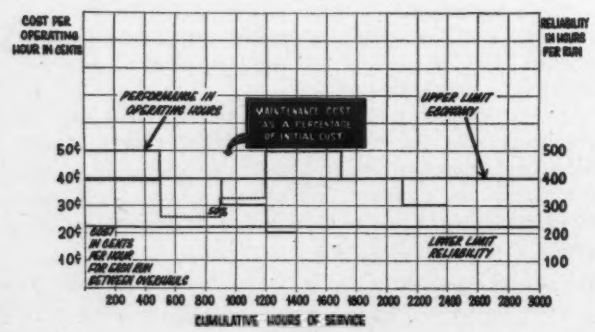


Figure 8

Decreasing reliability with repeated overhauls of an economically repairable component

Beginning with a 500 hour first run, the cost per hour of service is again 40c per hour. But since reliability is decreasing rapidly, several undesirable conditions appear:

(a) Because a trend of decreasing reliability is indicated, management must immediately take steps to establish a minimum acceptable limit below which reliability cannot be permitted to go regardless of cost or any other conditions

(b) The cost per hour of use, even if the cost of overhaul is only 50% of the cost of a new component, remains at an economical rate only for a limited number of overhauls.

While this is another hypothetical and totally unrealistic case, it also conveys a very definite impression of what may generally be expected if the overhaul process cannot retain the original level of reliability.

Ground rules for evaluation

In view of the conclusions that can be drawn from these hypothetical cases, it appears that acceptable ground rules and a formula for the evaluation of overhaul of electronic components can be stated more or less as follows:

(a) Since the performance of electronic components is erratic, the response of each component to its own overhaul process should be evaluated individually,

(b) In view of the devastating effects of decreasing reliability, a standard for reliability acceptable from overhaul should be set at 100% of the reliability of the new component

(c) Reliability must be measured accurately in terms of average per cent of TBO attained or in terms of mean time to failure. Compliance with quality control standards, which is quite adequate for other purposes does not seem to be acceptable for this decision process.

The continuation of extensive maintenance (or overhaul) is justified if

$$MTF_o \geq MTF_N;$$

Provided that

$C_o + C_H \leq C_N$, where

MTF_o = Mean time to failure of overhauled component,

N = New component,

C_o = Cost of overhaul, and

C_H = Cost of handling

Figure 9

A formula for the re-examination of overhaul

Bearing these restrictions in mind, the formula shown in Figure 9 should be adequate for the evaluation of overhaul effectiveness in the field of electronics and other fields where historical performance data is not readily available.

The general assumption behind all of this discussion is that disposal at failure would be the most desirable concept if the overhaul process cannot justify its continued existence in terms of retention of reliability, and economy in the cost per hour of use.

The upshot of this whole question of choosing between concepts does not appear to depend so much on the feasibility of the new concept as it does on the re-examination and rejustification of the old concept.

CONCLUSION

General

(a) The trend of the art is healthy – "ability to maintain" has been able to remain abreast of technological advance.

(b) As long as aircraft carry people aloft, caution will dominate maintenance policy – this means over-maintenance.

Repair and replace or rotable component concept

The repair and replace or rotable component concept

(a) has been the major factor in the advance of the maintenance art,

(b) has demonstrated the ability of maintenance to greatly increase the reliability of mechanical components,

(c) has, through its feed-back to industry, contributed substantially to the advance of technology, and

(d) is the most effective concept of aircraft maintenance that has been developed to date.

Disposal at failure concept

(a) Disposal at failure becomes feasible only as the result of modular design.

(b) Cheap modules make disposal at failure mandatory, whereas expensive modules make this concept prohibitive.

(c) In order to justify disposal at failure, it becomes necessary to show that maintenance is ineffective.

(d) Because maintenance is effective on mechanical devices, it remains desirable in aircraft maintenance.

(e) Disposal at failure may be effective for electronics.

(f) This poses the problem of using both concepts, which may detract from the advantages offered by disposal at failure.

REPRINTS OF PAPERS

Published in the Canadian Aeronautical Journal
can be obtained at the following rates

Length of Paper	1 to 3 pages	4 to 7 pages	8 to 11 pages	12 to 15 pages
100 copies	$26.00	$33.00	$39.00	$45.00
Additional 100	$9.00	$11.00	$13.00	$15.00

Orders for reprints should be addressed to the Secretary within 30 days of the date of issue of the Journal in which the paper appears. Orders for less than 100 copies cannot be accepted.

Revised October 1959

MAN-POWERED FLIGHT

The Regulations and Conditions governing the award of the £5,000 prize offered by Mr. Henry Kremer, which is to be known as the Kremer Competition, have now been laid down by the Royal Aeronautical Society and are as follows:

This Competition shall be conducted by the Royal Aero Club of the United Kingdom under the Regulations and Conditions laid down by a Committee called the KREMER COMPETITION COMMITTEE, which shall be composed of members of the Royal Aeronautical Society and of the Royal Aero Club. The Kremer Competition is hereinafter referred to as "The Committee".

NOTE: The Aircraft will be considered as Gliders and no Permit to Fly or Certificate of Airworthiness will be required. All intending entrants are strongly advised, during trials, to hold adequate insurance coverage for all Third Party Risks, and to take every precaution against damages to property.

REGULATIONS

(1) General

The prize will be awarded to the entrant who first fulfils the conditions.

(2) Prize

The prize is £5,000 sterling.

(3) Eligibility

The entrant, designer and pilot must be citizens of the United Kingdom or the British Commonwealth. The aircraft must be designed, built and flown within the British Commonwealth.

(4) Conditions of Entry

(a) Aircraft

(i) The machine shall be a heavier-than-air machine.

(ii) The use of lighter-than-air gases shall be prohibited.

(iii) The machine shall be powered and controlled by the crew of the machine, over the entire flight.

(iv) No devices for storing energy either for takeoff or for use in flight shall be permitted.

(v) No part of the machine shall be jettisoned during any part of the flight including takeoff.

(b) Crew

(i) The crew shall be those persons in the machine during takeoff and flight, and there shall be no limit set to their number.

(ii) No member of the crew shall be permitted to leave the aircraft at any time during takeoff or flight.

(iii) One handler or ground crew shall be permitted to assist in stabilizing the machine at the wing tip during takeoff.

(c) Ground Conditions

(i) All attempts which shall include the takeoff run, shall be made over approximtaely level ground and on a course to be approved by The Royal Aero Club.

(ii) All attempts shall be made in still air, which shall be defined as a wind not exceeding a mean speed of approximately 10 knots, over the period of flight.

(d) Course

(i) The course shall be a figure of eight, embracing two turning points, which shall be not less than half a mile apart.

(ii) The machine shall be flown clear of and outside each turning point.

(iii) The starting line, which shall also be the finishing line, shall be between the turning points and shall be approximately at right angles to the line joining the turning points.

(iv) The height, both at the start and the finish shall be not less than ten feet above the ground, otherwise there shall be no restriction in height.

(v) The machine shall be in continuous flight over the entire course.

(e) Observation

Every attempt shall be observed by the Royal Aero Club or by any body or persons authorized by the Royal Aero Club to act as observers.

(5) Application for Entry

(a) Entry forms shall be obtained from the Royal Aero Club, Aviation Centre, 19 Park Lane, W.1.

(b) The entry fee shall be £1 which shall be refunded upon the attempt taking place.

(c) Each application form for entry shall contain an application for Official Observation of the competitor's attempt.

(d) The fee for Official Observation shall be £15 15s. 0d. which shall be forwarded with the application form.

(e) The entrant shall undertake to abide by the conditions for Official Observation as set out on the application form and shall undertake to defray all expenses incurred in connection with the Official Observation of the attempt.

(f) Entry forms and applications for Official Observation of an attempt must be received by the Royal Aero Club at least thirty days prior to the proposed date of the attempt. Application will be considered in order of receipt at the Royal Aero Club Aviation Centre.

(6) General Conditions

(a) Insurance

The entrant must undertake to insure, on behalf of himself, his pilot(s), crew, representatives or employees, against third party risks in connection with the attempt to a minimum amount of £20,000. Evidence that such insurance has been effected must be produced to the Official Observers prior to the attempt.

(b) Eligibility

In any question regarding the acceptance of entries, eligibility of entrant, pilot, crew or aircraft under these Regulations, the decision of the Committee shall be final.

(c) Supplementary Regulations

The Committee reserves the right to add to, amend or omit any of these regulations and to issue Supplementary Regulations.

(d) Interpretation of Regulations

The Interpretation of these Regulations or any of the Regulations hereafter issued shall rest entirely with the Committee. The entrant shall be solely responsible to the Official Observers for due observance of these Regulations and shall be the person with whom the Official Observers will deal in respect thereof, or any other question arising out of this Competition.

(e) Revision of Regulations

These Regulations shall remain in force for a period of two years from the date of publication. After this time, the Royal Aeronautical Society reserves the right to review and amend these Regulations if the prize has not been won.

C.A.I. LOG

SECRETARY'S LETTER

MAN-POWERED FLIGHT

THERE have been stirrings in the realm of man-powered flight, brought about by the announcement of the Kremer Competition, which appears opposite[a].

When this Competition first came to my attention I wrote to the RAeS asking a few questions about such points as the arrangements for observers in this country. Then I sent copies of the announcement to some of our members whom I knew to be interested in the subject; some of these were members of the Soaring Association of Canada. Most fortunately the Soaring Association was about to hold its Annual General Meeting, and Mr. A. N. Le Cheminant, their President, was able to discuss the matter then and let me have a representative opinion of the gliding fraternity.

Others to whom I had written let me have their comments by mail and finally, on the 10th April, we held a meeting of people living in Ottawa, to study this correspondence and generally to decide what, if anything, should be done about it. We were very lucky in having Mr. B. S. Shenstone with us. Mr. Shenstone is not only an enthusiastic member of the CAI but a member of the Council of the RAeS and, as everybody knows, an outstanding authority on man-powered flight; he happened to be visiting Ottawa for the day and came along to our meeting. He could tell us about the various projects under way in England.

We concluded that it was perhaps not worthwhile to set out deliberately to compete for the Kremer Prize but it might be useful to find out the extent of interest in man-powered flight as such, in Canada, and try to co-ordinate it. To this end we set ourselves up as an unofficial committee, chiefly to provide a focal point and to meet from time to time to discuss progress. The members of the Committee are Dr. M. G. Whillans, Chairman, Mr. W. Czerwinski, Mr. A. N. le Cheminant, Mr. C. D. Long, Mr. B. S. Shenstone (as contributing member), and myself as Secretary.

What is the good of man-powered flight? Well, for one, there is Mallory's historic answer "'Because it's there". Secondly it has possibilities as a sport. Thirdly its pursuit will stimulate research in the low Reynolds Number regime, about which relatively little is known, and this, in turn, (though paradoxically dismissing the concept of man-power) may be of great benefit to soaring and to the re-establishment of the real light aircraft.

I shall be very glad to hear from anyone interested in this movement.

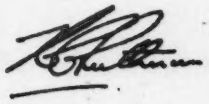
[a]Certain features of the announcement are not strictly applicable here and need to be Canadianized. For example, the Note at the beginning needs amendment; the aircraft would fall into the "ultra-light" category under Canadian regulations.

COMMUNICATION OF TECHNICAL INFORMATION

At the end of the last meeting of the Ottawa Branch, I was privileged to have an opportunity to consult the members about the art of communicating technical information. This is, of course, one of the primary functions of the Institute and, though it is essentially my problem, it is of basic interest to every member who wants to see his dues put to good effect. My introduction was based on a Report recently prepared under the auspices of the Guggenheim Foundation, which examined the existing galaxy of technical meetings in the USA and concluded by questioning whether the traditional devices for the communication of technical information, such as meetings and journals, which are manifestly overloaded, were not in fact inadequate to present conditions.

Although nobody came up with any revolutionary ideas – and I hardly expected that they would – some very interesting suggestions for the improvement of our meetings were put forward. These turned in the main on the provision of preprints of each paper, well in advance of the meeting, and their distribution to members known to be working in the field. In this way little more than a summary would be presented at the meeting, most of the time being devoted to discussion of comments and questions, either raised at the meeting or sent in beforehand by mail. The chief objection to this otherwise rather promising technique is the cost of preprinting; we have had to abandon preprints altogether for the time being for this very reason.

It would be most helpful to have suggestions from other members. We don't want stunts but we do want to improve our old methods of exchanging ideas and we want to supplement them with new and more efficient ones.



ANNUAL GENERAL MEETING

Programme

May 24th Morning 9.00 a.m.

BUSINESS MEETING

President

Dr. D. C. MacPhail
Director, Division of Mechanical Engineering,
National Research Council

Annual Reports of the Council
and of the various Committees

May 24th Morning 10.45 a.m.

MAN IN SPACE

Chairman
Dr. M. G. Whillans
Assistant Chief Scientist (Biosciences)
Defence Research Board

Future Uses of Space Vehicles

K. J. Radford
Director of Systems Evaluation, RCAF

Some Engineering Considerations for the Manned Space Vehicle

W/C R. A. Stubbs
O/C Flying Personnel Medical Establishment, RCAF

May 24th Afternoon 2.30 p.m.

HONOURS AND AWARDS

Chairman

Dr. D. C. MacPhail
President, Canadian Aeronautical Institute

Honorary Fellows

McCurdy Award

F. W. (Casey) Baldwin Award

and

The W. Rupert Turnbull Lecture

Development of Air Travel by Jet

A. E. Raymond
Senior Vice-President, Engineering,
Douglas Aircraft Company, Inc.

May 24th Evening 7.00 p.m.

DINNER

Chairman

Dr. D. C. MacPhail
President, Canadian Aeronautical Institute

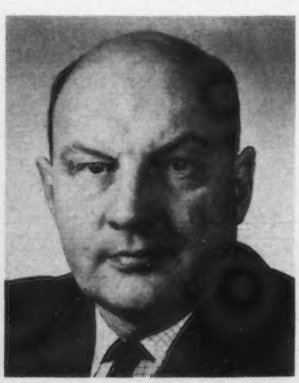
Address

F. T. Wood
President, Air Industries and Transport Association

K. J. Radford

W/C R. A. Stubbs

E. H. Higgins



T. A. Harwood

May 25th Morning 9.00 a.m.

AIR TRANSPORTATION AND THE CANADIAN NORTH

Chairman

R. B. McINTYRE

Assistant Engineering Director
The De Havilland Aircraft of Canada Ltd.

Modern Cargo Aircraft Design

E. H. HIGGINS

Chief Engineer, Aircraft,
Canadair Limited

Logistic Problems in the High Arctic with reference to Air Operations

T. A. HARWOOD

Head, Geophysics Section,
Defence Research Board

Recent Research in Arctic Meteorology

DR. S. ORVIG

Associate Professor of Meteorology
McGill University

ASTRONAUTICS SECTION

Chairman

D. BOGDANOFF

Chief Technical Engineer
Missiles and Systems Division,
Canadair Limited

Annual General Meeting — Business Session

May 25th Morning 10.45 a.m.

PROPULSION SECTION

Chairman

F. H. KEAST

Technical Director
Aeronuatical Group, A. V. Roe Canada Ltd.

Annual General Meeting — Business Session

May 25th Afternoon 2.00 p.m.

INDUSTRIAL

Chairman
P. W. LARSEN
Ottawa Representative, Aeronautical Group,
A. V. Roe Canada Ltd.

Reliability/Maintainability Engineering of Aircraft, Weapon and Electronic Support Systems

C. I. SOUCY

Air Materiel Command, RCAF

Short Run Production Problems

D. R. TAYLOR

Vice-President
Aviation Electric Limited

Engineers and Management

T. A. HARVIE

Assistant Chief Engineer, Administration,
Canadair Limited

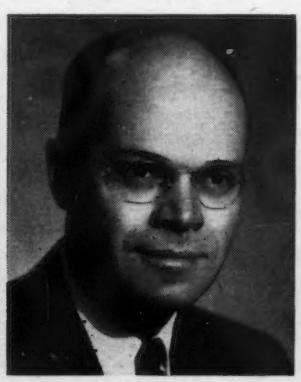
TEST PILOTS SECTION

Chairman
S/L O. B. PHILP
Director of Flight Safety, RCAF

Annual General Meeting — Business Session

Dr. S. Orvig

C. I. Soucy



D. R. Taylor

T. A. Harvie

MEETINGS

ANNUAL GENERAL MEETING

The programme of the Annual General Meeting is set out on the preceding pages; notices giving the full programme have been sent to all members of the Institute.

ABSTRACTS

The following are abstracts of some of the papers to be presented at the Annual General Meeting.

Future Uses of Space Vehicles

K. J. Radford–RCAF

This paper presents a review of the uses to which space vehicles may be put in the next decade. Both civil and military applications are considered and each is subjected to critical examination to determine whether the use of space vehicles provides significant advantages in system capability or economics. Conclusions are presented regarding the most promising space vehicle systems and particular consideration is given to those developments in which Canada might make a contribution.

Some Engineering Considerations for the Manned Space Vehicle

W/C R. A. Stubbs – IAM

This paper will present the available information on the requirements of man in the operation of space vehicles, in a form useful to the engineer. The cabin breathing air and the climate will be discussed and the limits for the total pressure and temperature of the breathing air and the partial pressure of its constituent gases will be discussed. The experimental work to determine the tolerances of man to the accelerations of rocket launch and atmospheric reentry will be reviewed and the limitations imposed by these accelerations on the physical and visual capabilities of man will be discussed. The progress of investigations to date on the effect of the weightless state and isolation will be briefly reviewed.

Modern Cargo Aircraft Design

E. H. Higgins–Canadair

One of the first and most important factors which must be established before proceeding with the design of any aeroplane is the definition of its payload. The difficulties which exist in defining and providing for the commercial cargo payload which can be expected in the future will be discussed.

Of particular concern to the cargo aircraft designer is the wide variation in cargo density as reported and predicted by the major cargo carriers. The required usable volume as recommended by various authorities varies by as much as 50%.

The tremendous potential traffic which the operating cost of the modern cargo aircraft will attract will be reviewed and Canadair's market research program will be outlined.

The performance and economics of the latest version of the CL-44 Swing Tail Cargo Aircraft will be described followed by a description of the features, which in the speaker's opinion, will be incorporated in the optimum cargo aircraft which can be expected to be in commercial operation in 1965.

Logistic Problems in the High Arctic with reference to Air Operations

T. A. Harwood–DRB

The author proposes to outline the historical development of logistics in the Canadian Arctic and in particular the Queen Elizabeth Islands. Some discussion will be made of the problems of sea transport, beach operations, sea ice conditions, the bearing strength of ice related to aircraft, and the problems of planning. The whole will finally be related to the loads required for a complex operation such as a Shoran survey of a seismic exploratory programme. Reference will be made to readily accessible sources of information.

Recent Research in Arctic Meteorology

Dr. S. Orvig–McGill University

A brief discussion of the history of arctic meteorology is followed by a more detailed description of research in Canada and other northern countries in the field of surface and high-level atmospheric phenomena.

An attempt is made to show the importance of such research in meteorology to northern transportation, both surface and air.

Reliability/Maintainability Engineering of Aircraft, Weapon and Electronic Support Systems

C. I. Soucy – AMC

Electronics has become a major factor in the cost and performance of aircraft and weapon systems and these require vast ground support systems. The accelerating increase in complexity of systems opposes the tactical necessity for increased dependability to meet fantastic space-age requirements for 10,000-to-one failure reductions. This requires mature man-equipment-environment-system design, with matching maintainability and reliability parameters, use of redundancy and breakthrough improvement of solid-state and other parts. Future goals and current achievements including extension of reliability techniques from the electronics to the mechanical field are examined.

Short Run Production Problems

D. R. Taylor–Aviation Electric

The objective of the Canadian Aviation industry is to find ways and means of manufacturing small quantities of equipment, which in many cases are of US design, at prices competitive with US prices. The ratio of Canadian production quantities to US quantities can vary anywhere from 1-5 to 1-20.

Efforts to achieve this objective can be accomplished by:

(a) Simpler tooling methods aimed at short run techniques.

(b) Use of high quality general purpose capital machinery offering the utmost in flexibility, rather than special purpose machinery.

(c) Careful planning to minimize machine set-ups and hence costs.

(d) Good organization in company overhead structure, in order to obtain maximum efficiency and minimum overhead rates.

(e) Employment of skilled labour to take advantage of human skills versus expensive tooling and machinery, where feasible.

(f) Last, but not least, "ingenuity".

Engineers and Management

T. A. Harvie–Canadair

"Why did Smith seem to falter when we moved him out of Engineering?"

"How come there are so many more accountants and lawyers than engineers in the front office?"

Questions like these are frequently raised by managers and engineers, indicating an awareness of the problem of the "Organization Engineer".

A great deal of attention is now being given to this problem, and it was felt that its discussion among members of the Institute might produce a general benefit.

To promote such discussion, an attempt will be made to outline the conflicting objectives of the managerial and engineering functions which, in the author's opinion, create operating difficulties. Some comment will also be made on the effect of the organizational environment on the individual engineer as a professional.

Finally some suggestions will be made as to what may be done to make engineers more manageable, and at the same time to make engineers better managers.

MEMBERS

NEWS

B. J. Kaganov, A.F.C.A.I., has resigned his position as Director of Research and Advanced Development at Canadair Ltd. to accept the appointment of Vice-President, Canadian Aviation Electronics Ltd., Montreal.

W. E. Armstrong, M.C.A.I., formerly with Avro Aircraft Ltd. has moved to Charlottetown, P.E.I., to take a position with Maritime Motor Supply Co. Ltd.

F/O D. M. McGregor, Technical Member, has recently resigned his commission with the RCAF to take a position with the National Aeronautical Establishment in Ottawa.

N. J. Thomas, Technical Member, has been transferred to the Engineering Dept. of TCA at Dorval Airport as Tyne Powerplant Engineer.

DEATHS

It is with deep regret that we record the deaths of **Mr. T. W. Emmerson, M.C.A.I.** and **Mr. P. K. Casey, Technical Member.**

Mr. T. W. Emmerson who died on the 30th March, 1960, was at the time of his death Assistant to the Sales Manager, Canadian Car and Foundry Co., Montreal.

Mr. P. K. Casey was at the time of his death, on the 17th April, 1960, Department of Transport Civil Aviation Co-ordinator.

ADMISSIONS

At a meeting of the Admissions Committee, held on the 21st April, 1960, the following were admitted to the grades shown.

Member

A. N. Lagopoulos, Chief, Engineering Projects, Olympia Airways, Greece: *Mithimnis 5, Athens (8), Greece.*

S/L P. McCracken, RCAF, OC Maintenance, CEPE Climatic Detachment, RCAF Stn. Namao, Alta.: *General Delivery, Lancaster Park, Alta.*

W. Robertson, Field Service Controller, Canadian Pacific Airlines (Repairs), Ltd., Calgary, Alta.: *7119 - 5th St. S.W., Calgary, Alta.*

G. G. Rezek, Production Officer, Dept. of Defence Production, Aircraft Branch, Room 401, No. 4 Temporary Bldg., Ottawa, Ont.

W. C. Rudderham, Assistant Chief Engineer, Fairey Aviation Co. of Canada Ltd., Dartmouth, N.S.: *55 Hazelhurst St., Dartmouth, N.S.*

M. Stade, Senior Engineer, Canadair Ltd., Montreal, P.Q.: *6120 Nelligan St., Apt. 6, Montreal 9, P.Q.*

D. R. Turner, Engineer A, Canadair Ltd., Montreal, P.Q.: *5077 Versailles Blvd., Pierrefonds, Montreal, P.Q.*

G. W. Walker, Chief of Quality Control, Canadian Pratt & Whitney Aircraft Co. Ltd., Montreal, P.Q.: *231 Percival Ave., Montreal 28, P.Q.*

G. F. Winham, Engineer, Canadair Ltd., Montreal, P.Q.: *1934 St. Germain Blvd., Ville St. Laurent, Montreal 9, P.Q.*

Technical Member

F/L H. L. King, RCAF, Test Pilot, CEPE Climatic Detachment, RCAF Stn. Namao, Alta.: *Box No. 3, Lancaster Park, Alta.*

W. Shelest, Inspector, De Havilland Aircraft of Canada Ltd., Downsview, Ont.: *83 Alexis Blvd., Downsview, Ont.*

W. W. Walker, Electronics Technician, Aviation Electric Pacific Ltd., Richmond, B.C.: *66 West 25th Ave., Vancouver 10, B.C.*

L. R. Ward, Jr., Mechanical Engineer, Canadian National Railways, Moncton, N.B.: *Lanchester Hall, College of Aeronautics, Cranfield, Bletchley, Bucks., England.*

Student

P. Boeuf, Ecole Polytechnique, Université de Montréal, Montreal, P.Q.: *925 Lecocq, Apt. 1, Montreal, P.Q.*

M. Ste-Marie, Ecole Polytechnique, Université de Montréal, Montreal, P.Q.: *Riviere-Gagnon, St-Jerome, Co. Terrebonne, P.Q.*

APPOINTMENT NOTICES

Service Representatives: several field service engineering positions are available to applicants with aero engine experience. Those selected will receive specialized training on gas turbine engines. Apply as below.

Technical Assistants: duties will involve liaison with aircraft operators and field representatives and the compilation of necessary reports and recommendations.

Applicants with a technical and practical background preferably in aeronautical (engine) engineering and educated to the Higher National Certificate standard should apply in writing only, giving qualifications and an outline of previous experience, to: Assistant Personnel Manager, Rolls-Royce of Canada Ltd., Box 1400 St. Laurent, Montreal 9, P.Q.

BRANCHES

Vancouver

Reported by J. W. Whiskin

March Meeting

Our regular March meeting was held on the 16th in the RCAF Officers' Mess, Sea Island. 29 members and guests were present.

Mr. Hartley took the chair for Mr. Hutton, the Branch Chairman, who was away on an extended business trip. During the business session all members were reminded that the next meeting was to be the Annual General Meeting, installation of officers and dinner and dance to be held at Canyon Gardens on April 23rd. Our Programme Chairman, S/L Falls, gave us the details for the tour of the US Aircraft Carrier, Coral Sea, which he had arranged for Saturday, March 19th.

S/L Falls introduced S/L C. C. Cooling who gave a most interesting talk on "The Role of the RCAF with the United Nations Emergency Forces in Egypt". S/L Cooling traced the history and development of friction between Arab Nationalism and Zionism from the 1917 Balfour Commission to the present time. He told us of the duties and responsibilities of the RCAF and UNEF, his own experiences and observations and followed his talk with coloured slides.

Mr. McWilliams thanked S/L Cooling for giving us a most interesting and enjoyable evening.

The meeting adjourned for refreshments and further discussion.

On Saturday, March 19th, over one hundred members and guests gathered at CPR pier B at 2.30 pm. We then boarded the USS Coral Sea for a very interesting tour of this tremendous ship. Unfortunately there were no aircraft on the ship but after walking for what seemed many miles, through the cavernous hangar, along the flight deck, up and down several dozen ladders and through countless corridors, it seemed the ship had everything else and everything was huge.

Halifax-Dartmouth

Reported by J. Milman

February Meeting

The February meeting of the Branch was held at St. Mary's University, Halifax, on Wednesday 17th February, 1960. The Branch Chairman, Mr. R. Wallworth, was in the chair. 39 members and guests attended the meeting.

The speakers, Professor K. Duggan of Nova Scotia Technical College and Mr. Brown of Nova Scotia Light and Power, were introduced by the Chairman. The subject of their talk was "Electronics Digital Computer".

Professor Duggan read the first part of the talk, entitled "Functional Aspects of Computers", and Mr. Brown the second part, entitled "Preparation Necessary for Dealing with Problems". The talk was illustrated by the Royal McBee LGP 30 Digital Computer owned by St. Mary's University.

After a long and lively question period, the speakers were thanked by LCDR G. M. Cummings, RCN. In his concluding remarks, the Chairman stated that he wished to thank St. Mary's University for allowing the Branch to hold the meeting there and to see their computer.

Winnipeg

Reported by C. P. Gulland

March Meeting

45 members and guests attended a Dinner Meeting held at the Winnipeg Flying Club on Tuesday, March 29th, 1960. In the absence of the Branch Chairman, Mr. B. W. Torell, W/C C. J. Evans took the chair.

Mr. J. Sears introduced the speaker of the evening, Mr. A. W. Fia, Chief Design Engineer of Bristol Aero-Industries Limited. Mr. Sears' brief résumé of the speaker's background showed that Mr. Fia was well qualified to speak on his topic for the evening, "Some Aspects of Rocket Development".

The speaker opened his address with a summary of the effect that the launching of Sputnik I had on the free world. Using statements made by eminent Americans, Mr. Fia showed reasons why the USA is pursuing its space program with such vigour. Directing his remarks toward the Canadian contribution of space exploration, Mr. Fia, in expressing the conviction that Canada should be doing experiments on her own, said: "There would appear to be a need for a truly national effort which would serve also as a means of self-expression for our own scientists and engineers. This would be a progam which would be all Canadian from the launching site and rocket to its instrumentation and measurements obtained. Some nations who are not so favourably located as we are, or who do not have our standard of living or as bountiful a share of the natural resources, consider it essential to have a National Space Program. The French have fired a number of vehicles of their own design and development; the Japanese, who built two types of rockets which they have fired successfully, are in the process of developing larger rockets for this use".

The speaker concluded his paper with the use of slides to show the various types of rocket motors presently in use or being developed.

A film, "Frontier Beyond the Sky", showing the work done in Churchill, Manitoba, for the IGY, concluded the evening. Mr. J. G. Davidson thanked the speaker.

Toronto

Reported by C. F. de Jersey

March Meeting

Mr. E. V. Claxton of General Electric had been invited on behalf of the Propulsion Section, Toronto Branch, to speak to the Branch on Thursday, 24th March, 1960; however he was unfortunately unable to attend, and his company selected Mr. R. Prior to represent them in his stead.

Mr. V. E. Crompton, Orenda Engines Ltd., introduced Mr. Prior to the audience of 205 members and guests, assembled in The De Havilland Aircraft Cafeteria. Before getting to the meat of his introduction, Mr. Crompton wetted the appetite of the audience by showing a film called "The J79".

This excellent film describing the engine and also its installation in the F104 Starfighter aircraft was, however, no match for Mr. Prior; in recounting the titles and achievements credited the speaker, Mr. Crompton mentioned his decade in the USAF, where he attained the rank of Major, his 3,500 hours in jets, his historic first crossing of the North Atlantic in an F86, his surviving 26 dead stick landings in jets and many others. He then spoke of Mr. Prior having joined the General Electric Company in 1952 and of his progress to his present responsibilities as Manager of their Flight Test Division.

Mr. Prior opened his remarks by relating the history of the J79 family of

engines from the beginning in 1942 with a development of the Whittle design called the 1A engine. Aided by some very good slides, the speaker described the various stages of development involving, amongst many other major items, the high pressure compressors, the variable stators and the completely modulated after-burners, all of which provided a Mach 2 engine having an unprecedented thrust/weight ratio.

Great flexibility, economical operation and a considerable reduction in weight was achieved, resulting in an engine of about the same weight as the J47, but producing double the thrust.

The J79 has been developed for use in a number of aircraft, notably the Convair B58 and the McDonnell F4H fighter, the latter having set an altitude record by reaching some 98,000 ft, was promptly sidelined by another J79 powered aircraft, the F104, which lifted the peak to 103,000 ft.

Future installations include the B70, a Mach 2-plus project using a development of this engine, the J93.

Mr. Prior summed up his talk by mentioning other projects wherein the J79 was either used or envisioned, such as mobile power units, mobile emergency power supplies transported by either rail or road and finally the Grumman Hydrofoil boat weighing 80 tons and capable of speeds of 80 knots!

It is possible that the speaker felt that he had now covered the field and was, therefore, due for a rest; this was wishful thinking, with a speaker of Mr. Prior's calibre, the audience had no intention of letting him go.

It was obvious that the J79/F104 association was of the greatest interest to the audience; the speaker's immense experience with both the aircraft as such, and the engine, raised a barrage of questions keeping Mr. Prior on his toes for a further forty-five minutes before Dr. Wade lowered the boom.

Rumours of the aircraft behaving like an unguided missile, were quickly dispelled by the speaker who felt that the flying characteristics could be favourably compared with the F86, requiring very little effort; in fact, there was no difference in feeling between Mach 1 and Mach 2, except that all the needles moved a little faster!

Fears that the downward ejection was an automtaic pass to the undertaker were also quashed by Mr. Prior. He stated that there had been several successful ejections; one, he believed, had been effective from as low as 600 ft.

In answering final questions, Mr. Prior said that neither the F104 nor the J79 should present any problems in maintenance or servicing to qualified personnel; this is of course borne out by their impressive record upheld to date.

Mr. B. A. Avery, Vice-President and General Manager of Orenda Engines, was asked by the chairman to move the vote of thanks, after which Mr. Prior was allowed to leave the dais, but not the floor, where he was besieged by members and guests alike until the lights were switched off!

Ottawa

Reported by A. N. le Cheminant

March Meeting

The regular monthly meeting of the Branch was held at the Officers' Mess, Gloucester Street, on Wednesday, the 16th March with the Branch Chairman, CDR N. A. Smith, presiding.

F/L Bell informed a gathering of some 70 members that, unfortunately, Dr. Bertelsen of Bertelsen Manufacturing Company, who was to have talked on the subject "Aeromobile–A Ground Effect Machine", would not be able to attend due to bad weather but hoped that an opportunity would occur some time in the future. He then introduced Mr. Stepniewski who is, of course, an old friend of many Canadians. His talk, extremely well illustrated by both slides and a film, gave an idea of the amount of work that had already gone into the proposal of utilizing the ground effect cushion as a means of eliminating aircraft undercarriage gear. His paper was based on one presented at the Symposium on Ground Effect Phenomena at Princeton University in October, 1959. It would seem that a whole new field of endeavour was opening up and that careful consideration of optimizing the many parameters could result in an economic concept which would have practical value.

The question period was noticeably slower, due to a reflection on the completeness with which the subject had been presented or a hesitancy to embark on a subject with which a lack of familiarity had been made evident by the material presented. Mr. Stepniewski's sincere enthusiasm for his subject was certainly apparent and it was pleasing to note a remark that there was a possibility of Canadian participation in some of the test work in the future because of changes now underway at the NAE low speed tunnels.

Mr. J. L. Orr ably thanked the speaker on behalf of the Branch, winding up another successful evening.

April Meeting

The regular meeting of the Branch was held on Wednesday, 13th April, with the Chairman, CDR N. A. Smith, presiding. The planned program was to some extent spoiled by the bad luck which has dogged Dr. Bertelsen's paper on a Ground Effect Vehicle. His film, received that day, was found to have been stripped of sprocket holes by a previous exhibitor and, thereby, made its showing impossible. Dr. Bertelson's paper "Design of Ground Effect Vehicles" was available in quantity for those attending. F/L Bell explained Dr. Bertelson's philosophy and then narrated while the Bell film on the fibreglass constructed plenum chamber air cushion scooter was screened.

Following the film, which well portrayed the possibilities and some of the limitations of the vehicle, a lively discussion took place.

After the recess period, CAI Secretary, Mr. H. C. Luttman, opened what proved to be a most interesting discussion. Basing his opening remarks on a report entitled "Technical Meetings in the Flight Sciences" made by a commercial organization for The Daniel and Florence Guggenheim Foundation, Mr. Luttman expressed belief that to a lesser degree similar feelings to those expressed in the report existed in Canada.

The report stemmed from apprehension that too many meetings, seminars and conventions were being held in the Flight Sciences field, leading to a possible duplication of papers on similar subject matter. The report concluded that duplication did not exist to any marked degree, but that a new medium for disseminating technical information was highly desirable and that the traditional means of presentation by papers was not adequate for the present rapidly changing times. One sound suggestion which found favour among those present did not provide any new or novel approach, but would be helpful; this was that of preprinting papers and issuing them some weeks in advance. This would give much better opportunity to raise questions, analyze and have the speaker answer at the presentation. Unfortunately our current financial situation would seem to preclude preprinting.

A pleasant evening was enjoyed by the rather few (30 odd) members who attended.

The vote on the Student amendment introducing Article 8 to the Branch Bylaws was carried very heavily by a vote of 80 affirmative, 2 against and one spoiled ballot.

SECTIONS

ASTRONAUTICS

Newsletter No. 2

by Dr. H. J. Luckert

Less than three months have passed since the first Newsletter was issued. For a new organization such as the Astronautics Section of the CAI, this is a short period, with regard to activities which represent a big step forward in the development and progress of such an association.

Nevertheless, some activities have taken place on the Montreal stage, and it seems worthwhile to report on them. It is evident that spectacular events on the national scene cannot happen too often and the main efforts in Section activities must be centered in the local units; here, in fact, the life of a Section is shaped, with proper direction, guidance and co-ordination, of course, through the Executive Committee. For it is only here, where all the members of a Group can meet frequently, that interest can be furthered and progress achieved.

Formation of local Groups

For the reason outlined above, the formation of local Groups, where this is possible, cannot be recommended too strongly. As stated in the first Newsletter, however, a Group does not exist on paper alone – activities are imperative. The first step here is to arrange informal get-togethers, in the form of short Discussion or Lecture Evenings. In Montreal this experiment has been made, and with a satisfactory degree of success.

Some informality is one point which plays an important role – it not only facilitates the active participation of all, in particular the junior members, but also it furthers the aim of stimulating all members to play a part by making contributions in their particular fields of interest. Experience in Montreal has confirmed this.

This Discussion or Lecture Evening technique should in general start by the presentation of basic principles of a topic. Lectures only half or badly understood do more harm than good. The level, of course, should be appropriate to the composition of the convening group. As a matter of fact, however, the fundamentals cannot be stressed too much, in order to obtain a reasonable background for proper understanding of the matter. There is no doubt that after emerging from the initial "trial" phase, the level will rise automatically.

News on Local Activities

Ottawa

The Ottawa Group, which now has 28 members, reports on a Branch Meeting addressed by Dr. de Vaucouleurs on the 24th of February. A summary of this address was published in the last issue of the Journal. The lecture, which dealt with the Atmospheres of Venus and Mars, was also given in Montreal the day before, as reported below.

Toronto

Toronto, with 15 members, had planned a meeting in April to be sponsored jointly by the Toronto Branch of the CAI and the UTIA. However, this lecture has been postponed due to changes in the Branch programme.

Montreal

The Group now has 30 members.

(1) Astronautics Section Dinner Meeting, February 1960

Dr. Gerard H. de Vaucouleurs, at present Research Associate at the Harvard College Observatory in Cambridge, Mass., addressed the Meeting held on the 23rd February at Canadair. The visit by this outstanding French astronomer and astrophysicist to Montreal and Ottawa was sponsored by Canadair Ltd.

With the present increasing emphasis on space science and the advance in the technology of space vehicles, the possibility of exploration of the nearest planets is within sight. The lecture on the "Atmospheres of Venus and Mars" was therefore stimulating, informative and timely.

Some publicity was given to this lecture by television and the Montreal press. Dr. de Vaucouleurs was interviewed by CBC and appeared on the "Carrefours" program of the French television network. La Presse and Le Devoir mentioned his lecture in short notes.

A short report on the meeting was published in the April issue of the Journal. Some more information on the topic can be found in Astronautics Note No. 4, which has been distributed to the members of the Section.

(2) Montreal Group Discussion and Lecture Evenings

As mentioned in the first Newsletter, the second Discussion Evening was to take place in *February*. It was held on the 9th of February on the subject "Fundamentals of Orbital Mechanics". The main lecture (by D. Ellington, Canadair) dealt with gravitation, escape and circular velocity, lifetime of a satellite, orbital characteristics and the effect of launching inaccuracies. Also, a review was given of vehicles launched to date. A further contribution on "Mathematics of Elliptic Orbits" (by H. J. Luckert) showed that very many interesting problems can be solved by elementary mathematics. The "Proceedings" of this Discussion Evening are given in Astronautics Note No. 3.

From February on, the Discussion Evenings are on a monthly schedule, taking place the second Tuesday in every month. The *March* meeting (8 March 1960) had as its theme "Some Guidance and Control Problems Associated with Satellites". The discussion dealt with launching and powered flight control problems, the guidance into orbit, control in orbit, and problems in recovery. Some discussion followed on possible practical application for satellites. An Astronautics Note on this subject (No. 5) is in preparation.

The *April* meeting (12 April 1960) was devoted to "A Description of the Planets of the Solar System". The lecture, given by B. Myers, Canadair, attempted to present the planets as seen by the astronomer. It gave descriptions of the observational data that have been recorded and the deductions made from these data, leading to the present theories regarding the form and make-up of the planets. About 30 people attended. Astronautics Note No. 6 on this lecture is also in preparation.

The Montreal Group plans to have the *May* meeting on "Properties of the Upper Atmosphere". Topics for the following months will be Aerodynamic Heating, Gravity, Propulsion Devices, etc.

(3) Lecture on "Flight into Space" at McGill

Though not a direct Astronautics Section activity, it is worthwhile to mention this lecture, on the 10th March, which was given in the lecture series of the McGill University Symposium on Flight, and which was attended by a number of members of the Astronautics Section. The lecturer was W. F. Campbell of NAE who, following the intention of this Symposium to address in popular lectures people with an interest in aviation but not necessarily a scientific training, gave an interesting presentation of the subject of space flight.

Astronautics Notes

As has been mentioned, the Montreal Group issues Astronautics Notes, four of which have already been distributed. These Astronautics Notes are to fulfill a two-fold purpose. The spoken word in the lectures and discussion certainly arouses interest, but a number of details cannot be remembered, and only the written note can deepen the knowledge and actually further the proper understanding of the subject. In addition, they enable the members who could not attend the meeting, and members of other Groups, to be informed about various subjects and all activities.

It will be observed, and perhaps complained about by some members, that the presentation is somewhat elementary. This is partly inevitable, partly held so on purpose. The activities of the Section try to appeal to the large majority of the members to stimulate their interest and to give them broad knowledge of the fundamentals. On the other hand, it is most essential, as already pointed out at the beginning, that the basic principles are understood.

So far, the following Astronautics Notes have been issued by the Montreal Group:

No. 1: Some Notes on Dispersion (by E. Bendor)

No. 2: Re-Entry (Notes on lecture given by M. B. T. George)

No. 3: Fundamentals of Orbital Mechanics:

Part I–Elements of Orbital Mechanics (by D. Ellington)

Part II–Mathematics of Elliptic Orbits (by H. J. Luckert)

No. 4: The Atmospheres of Venus and Mars (by L. Pon, based on lecture given by G. H. de Vaucouleurs)

In preparation:

No. 5: Some Guidance and Control Problems Associated with Satellites (by E. Semple)

No. 6: A Description of the Planets of the Solar System (by B. Myers)

Again all Groups and individual members are encouraged to report on events, lectures or studies which are of general interest to all members of the Section, in the form of Astronautics Notes.

Meeting of the Executive Committee

A meeting of the Executive Committee of the Astronautics Section took place at CAI Headquarters in Ottawa on March 21, 1960. On the Agenda were among others, suggestions for the Executive for the coming year, plans for the Annual General Meeting in May, and the Symposium on Canadian High Altitude Research which is planned for the Fall. Details on these subjects are given below.

Annual General Meeting of the CAI

This Meeting is scheduled for May 24th and 25th in the Chateau Laurier, Ottawa. A half day session is reserved for "Man in Space" when two astronautics papers will be given.

The Annual Business Meeting of the Section is to be held in the morning of May 25th. The retiring committee will present the report on the past year, and the new Executive Committee will be introduced. Suggestions for the new organization of the Section will also be discussed.

Symposium of the Canadian High Altitude Research Program

The plans for this Symposium are progressing well. It is to be held in the Fall, tentatively scheduled for the 20th and 21st October in Ottawa, with approximately nine papers given during the first three half-day sessions, and a round table discussion during the final half-day session. A tentative list of speakers and topics for the Symposium has already been compiled by the Executive of the Section. More details will be announced in following Newsletters.

The Executive Committee, and Organization Plans for the Section

In distributing the nomination papers, preparatory to the election of Section Officers for 1960-61, the Secretary of the CAI passed on a recommendation from the Section Executive Committee to the effect that in future all members of the Committee (except the Past Chairman, of course) should reside in the same city. This would considerably facilitate the conduct of the Section's business. The places chosen for the Committee will be changed from year to year in an agreed order of rotation, i.e. at present Ottawa, Toronto, Montreal, where the conditions for the formation of Groups are already fulfilled. However other cities will be brought into the circuit as the membership of the Section living in these cities increases.

The place suggested for the coming Executive is Ottawa.

In the past, the members of the Executive Committee have usually lived in different places. This was useful during the first years of the Section's existence, the period of "establishing" the Section, as it gave the various Groups a certain degree of representation. However, the drawbacks of this arrangement are evident as already mentioned, and since the Section is now much more established, a "Central Government" is preferable. This entails now, of course, the necessity of local leadership and it was suggested for this reason that Chairman of the Groups should be elected by the Groups every year. (For this year only, the Group Chairmen are to be appointed by the new Executive.) Thus the Group Chairman would be responsible to the Section Executive Committee for proper coordination and the conduct of local affairs. It seemed also desirable that the Group Chairmen represent the Groups in the respective Branches, so as to guarantee cooperation between the Section and the Branches.

All these proposals require a change in the Regulations of the Section, and the members will be asked for their approval of the changes at the Annual Business Meeting of the Section on May 25th. For this reason members are asked to attend this meeting.

Concluding remarks

This Newsletter has tried to keep the members up to date in the development of the Section. It must be remembered, however, that for a Newsletter to form a true communication between all members, the cooperation of all Groups and individual members is necessary. For the Astronautics Section is not the Executive Committee but its total membership. Inquiries, comments and contributions are therefore very welcome.

The next Newsletter is intended to be issued in June, so that the members who were not able to attend the May Meeting may be immediately informed about the affairs of the Section.

BOOKS

Foundations of Aerodynamics — Second Edition. By A. M. KUETHE AND J. D. SCHETZER. John Wiley & Sons, New York, 1959. 446 pages. Illus. $11.75.

University teachers and others who have used the original version of this book for introductory and intermediate courses in aerodynamics will welcome the new edition. It has benefited by numerous detailed revisions and by the relegation of sections containing aerodynamic data and tables to appendices. These revisions, aimed at putting more emphasis on compressible viscous flow, include a more detailed treatment of the energy equation (Chapter 8) and compressible flow over lifting surfaces (Chapter 11), the addition of a new chapter on the compressible laminar boundary layer (Chapter 14) and a discussion of the coefficient of thermal conductivity in the section on molecular transport properties (Chapter 1). Other useful short sections, discussing the approximations inherent in Prandtl's so-called lifting line theory, the Falkner-Skan similarity solutions for the laminar boundary layer, and one dimensional flow with friction and heat addition, have been added. The author's concession to modern trends, which incidentally enables the publisher to claim that the book concerns Space Technology, is an Appendix (D) on real gas effects, which very briefly considers a few aspects of high enthalpy flows and gives many excellent references.

The treatment of the compressible turbulent boundary layer and Reynolds' analogy, covered in three and a half pages, is rather inadequate, and the discussion of shock-wave boundary-layer interaction out of date. The former topic is rather empirical and difficult from a teaching point of view and one is tempted to omit it altogether, but its engineering importance demands treatment consistent with the other topics discussed.

Apart from these comparatively minor limitations, this is a valuable and well-balanced text book on the fundamentals of aerodynamics, and will continue to be of great assistance to undergraduate and graduate students in this field.

W. J. RAINBIRD

Theory of Mechanical Vibration. By K. N. TONG. John Wiley & Sons, New York, 1959. 348 pages. Illus. $9.75.

This book provides an interesting illustration of the manner in which analytical techniques are developing as research in applied mathematics becomes available and the approach to "classical" problems becomes more sophisticated. The author states at the outset that his aim is to provide a text or reference for graduate students in a theory-centred rather than an engineering course and he has followed this aim faithfully as there are virtually no practical problems used to illustrate points in the theoretical development as are found in previous texts on this subject. He has, however, succeeded in introducing analytical concepts which are currently of increasing use in practical engineering, so that the book should be of value to the practising engineer working in the field of dynamics.

The book is divided into four chapters, with most of the analytical procedures introduced in the first. One is tempted, when reading the index, to dismiss the work as just another text, as the chapter titles are effective cloaks. However, the subject is developed in a logical manner, and when the end is reached, the careful reader, if he has been prepared with a proper mathematical grounding, will find himself well equipped to embark on dynamic analyses.

Chapter one is inocuously titled "Systems with a Single Degree of Freedom". It is however, no mere rehashing of the standard "mass on a spring with viscous damping", although this is the basic representation. The modern mathematical approach is immediately apparent. In addition, the reader is introduced to the Fourier representation of random excitation, the concept of the transfer function, the nonviscous dampings and the idea of a complex stiffness. The problems at the end are carefully chosen to illustrate the theory rather than to represent "practical" systems but a thorough grounding is provided, and the rest of the book should prove straightforward.

The second chapter deals with two degree of freedom systems in the same thorough manner, the principal introduction being the representation of stiffness by influence coefficients. The next chapter proceeds to study many degrees of freedom and here matrix notation is introduced as the mathematical tool to handle the concepts outlined earlier. The reader must be somewhat familiar with matrix manipulation before using this book however, as this familiarity is presupposed.

The final chapter moves on to the study of elastic bodies as the limiting case of vibration analysis. Wave phenomena are treated here as well as the extensions of the work of the previous chapter. The most interesting new concept is that of analysis by the finite difference approximation to the differential or integral equation.

The book concludes with a brief appendix containing the matrix background required for chapter three. In sum, it is a book designed to stimulate thought rather than to provide methodology and in this purpose succeeds very well.

J. A. MCKILLOP

Guide to the Space Age. By C. W. BESSERER AND H. C. BESSERER. Prentice-Hall Inc., New York, 1959. 320 pages. Illus. $7.95.

This new book presents in clear and simple language the terminology used in the fields of space technology and guided missiles.

The authors have attempted to help standardize the specialized language and scientific jargon used in this new field, and present the material in such a manner that the layman will understand.

The terms are listed alphabetically with a system of cross reference to guide the reader to the exact nomenclature and position of standard scientific terms. Mathematical expressions are kept to a minimum. Drawings and diagrams are used wherever possible to clarify the descriptions or concepts.

The only major deficiency the book has is an almost complete lack of acknowledgement to the Russian field of endeavour. Sputnik I, the first satellite put into orbit, has been completely ignored together with subsequent Russian accomplishments – not to mention other countries engaged in space technology.

In general, the book deals with the efforts being made in the USA. However, it should be pointed out that this edition is the first and if expanded and kept up to date by constant revision it would prove moderately useful to technical personnel engaged on the fringes of space technology.

W. A. CHISHOLM

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The Canadian Aeronautical Institute invites the submission of papers, articles and technical notes for publication in the Canadian Aeronautical Journal. Following the practice of other societies, the Institute does not pay for contributions.

Authors should prepare their material in accordance with the following directions:

Manuscripts. Manuscripts should be
(a) Typewritten, double-spaced,
(b) On one side of 8½ x 11 white paper,
(c) With wide margins, approximately 1½", and
(d) With pages numbered consecutively.

Manuscripts must be in final form; the addition of material after acceptance by the Institute cannot be permitted.

Titles. The following form should invariably be adopted:—
(a) Titles should be brief;
(b) The name and initials of the author should be written as he prefers; (Rank or title preceding the name e.g. Wing Commander or Dr., should be included but abbreviations of degrees etc., after the name, should be omitted.);
(c) The name of the organization with which the author is associated should be shown under his name; and
(d) The author's position in the organization, referred to in (c) above, should be shown as a footnote to the first page.

Summaries. Each paper should be preceded by a summary
(a) Of 100 to 300 words, (10 to 35 lines, double-spaced),
(b) In non-specialist language, so far as possible,
(c) Stating the main conclusions of the paper.

Sub-Headings and Paragraph Numbering. Sub-headings should be inserted by the author at frequent intervals. Paragraphs should not be numbered.

References. References referred to by the author should be treated thus:—
(a) References should be numbered consecutively throughout the paper;
(b) An allusion to a reference should be indicated by a bracketed numeral e.g. "It has been shown by Dr. T. T. James (7) . . . ";
(c) Direct citation of a reference in the text should be written in full, e.g. "As shown in Reference (7) . . . "; and
(d) References should be grouped together in numerical order at the end of the paper, each showing
first, the numerical designation, e.g. "(7)".
second, the author's name, e.g. "James, T. T."
third, the title of his work, e.g. "Aerodynamics and Ballistics"
fourth, the title, volume, issue no, and date identifying the publication in which it appeared, e.g. "R.B.S. Journal, Vol. 7, No. 77, July 1907".

Thus "(7) James, T. T.,–Aerodynamics and Ballistics, R.B.S. Journal, Vol. 7. No. 77, July 1907."

Footnotes. Comments on or amplification of the text should be given in footnotes, appearing at the bottom of the appropriate pages.
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(a) Figures and Tables should be given in full, e.g. "Figure 7", but
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Symbols and Abbreviations. Consistency is important;
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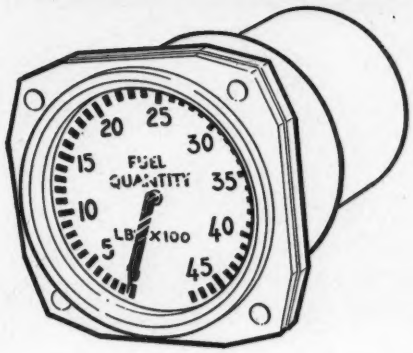

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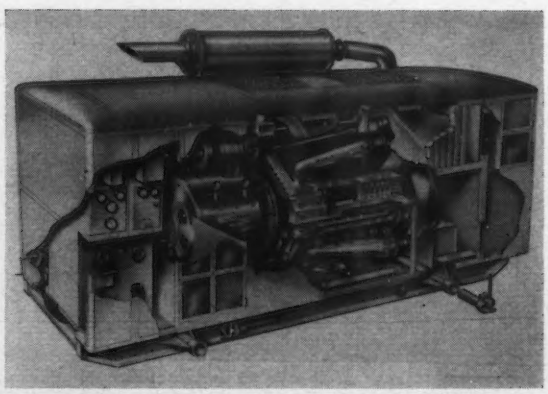

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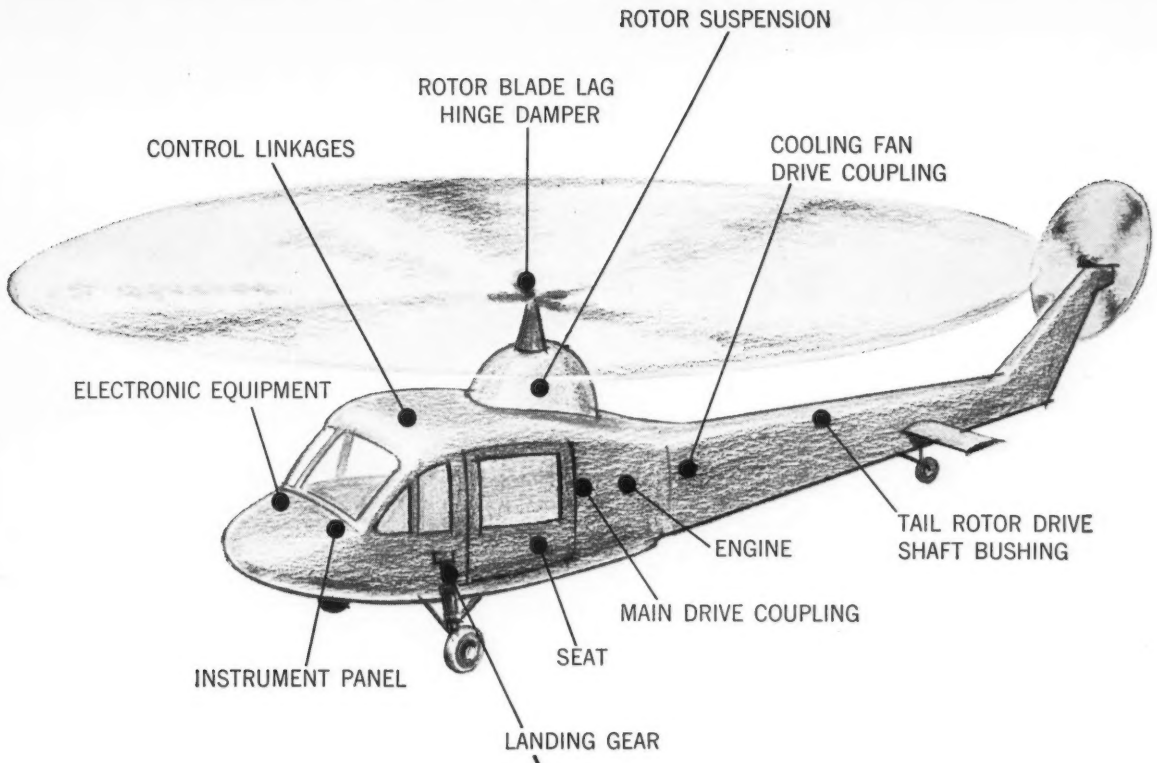

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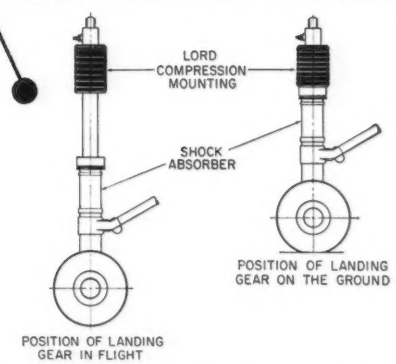

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